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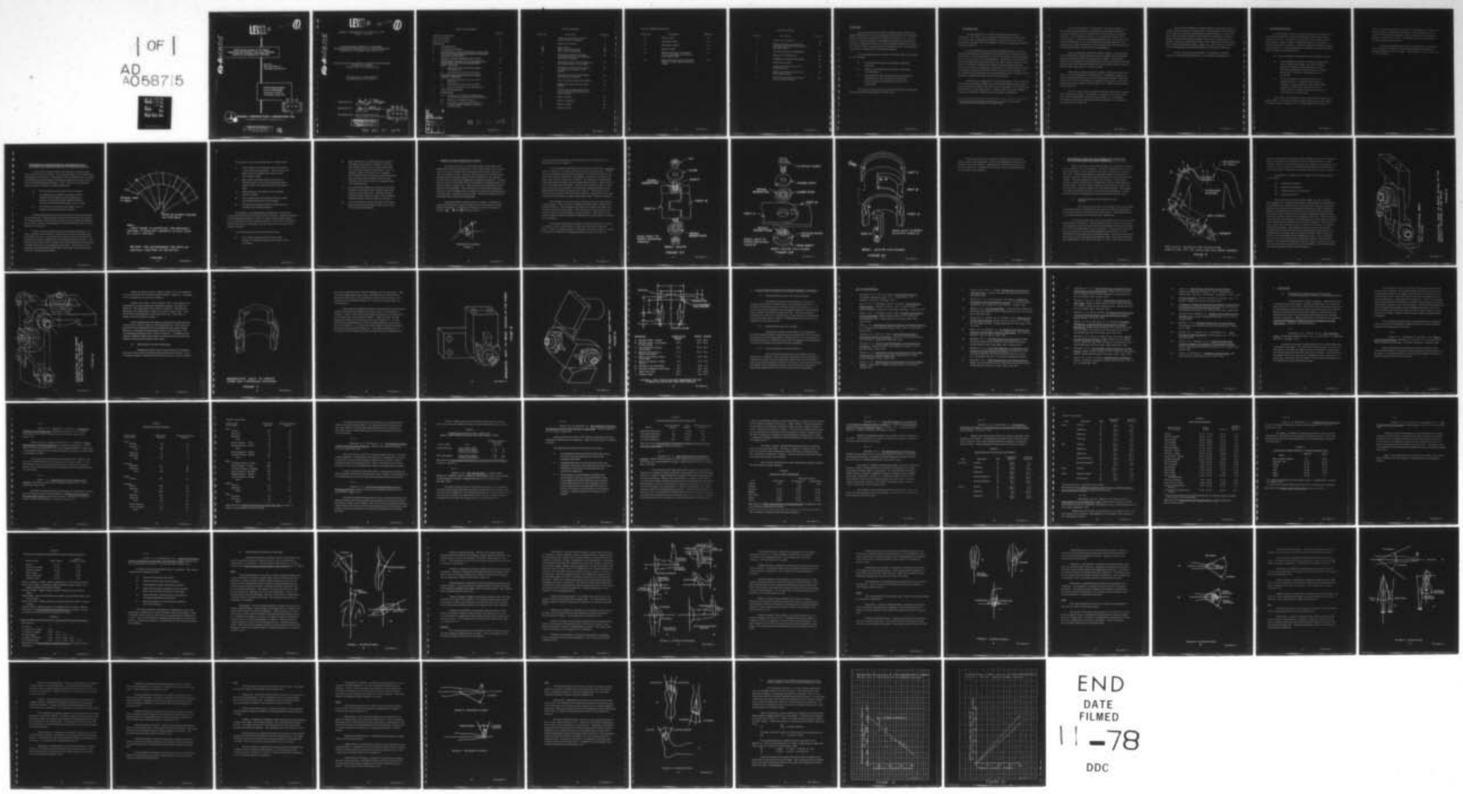

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INVESTIGATIONS LEADING TO THE DESIGN, FABRICATION AND TESTS OF A FULL-SCALE WEARABLE MOCKUP OF AN EXOSKELETAL STRUCTURE

Prepared for:
Office of Naval Research
Psychological Sciences Division

INTERIM TECHNICAL REPORT
Contract No. NONR-3830(00)
CAL Report No. VO-1692-V-1
16 April 1962 to 1 October 1962

CORNELL AERONAUTICAL LABORATORY, INC.
OF CORNELL UNIVERSITY, BUFFALO 21, N. Y.

LEVEL II

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CORNELL AERONAUTICAL LABORATORY, INC.
Buffalo, New York

INVESTIGATIONS LEADING TO THE DESIGN, FABRICATION AND TESTS OF A FULL-SCALE WEARABLE MOCKUP OF AN EXOSKELETAL STRUCTURE

INTERIM TECHNICAL REPORT COVERING PERFORMANCE
DURING THE PERIOD
16 APRIL 1962 TO 1 OCTOBER 1962

CONTRACT NO. NONR-3830(00) new
CAL PROJECT NO. VO-1692-V-1

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Psychological Sciences Division

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FOREWORD

This interim technical report is submitted under Contract No. NONR 3830(00) between the Psychological Sciences Division of the Office of Naval Research and Cornell Aeronautical Laboratory, Inc., wherein CAL is to conduct preparatory investigations leading to the design of a full-scale, wearable, mock-up of a non-amplifying exoskeleton, as part of a research task to further assess the feasibility of the "man amplifier" concept and to implement its ultimate development.

The investigations are to include, but not necessarily be limited to, the following:

a) A comprehensive search of available, applicable literature

b) Studies of individual joint mechanisms and human body kinematics

c) Development of sketches and layouts of mechanical components for joint mechanisms which most nearly simulate the motions of the joints of the human body.

This interim technical report reviews progress achieved during the period 16 April 1962 through 1 October 1962.

1. INTRODUCTION

The Man Amplifier, as conceived by Cornell Aeronautical Laboratory, Inc. (CAL), is an exoskeleton employing powered joints that is worn by a man to augment and amplify his muscular strength, and to increase his endurance in the performance of tasks requiring large amounts of physical exertion.

In the developed concept, the Man Amplifier consists of a basic structural exoskeleton with appropriate articulated joints compatible with those of man. All external loads, as well as the weight of the Man Amplifier itself, are borne by this structural skeleton. Each joint is powered by one or more servomotors which provide the necessary torques and power boost. These servomotors respond to the outputs of sensors linking man and machine, and cause the appropriate mechanism to follow the natural motion of its human counterpart with little effort on the part of the operator. In the original concept a portable, self-contained power pack is attached to the back of the exoskeleton to provide the necessary power.

Preliminary investigations* of the Man Amplifier concept consisted of (1) analytical studies to define some of the major problem areas which must be examined in detail before the technical feasibility of the concept can be established, and (2) experiments, using the CAL elbow-joint amplifier, to obtain a preliminary indication of man-machine compatibility.

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* Sponsored by the Aerospace Medical Division, Air Force Systems Command under Contract No. AF 18(600)-1922.

It was concluded that: (1) duplication, in the Man Amplifier, of all the human motion capability is impractical, (2) experimentation is necessary to determine the essential joints, motion ranges and dynamic responses, (3) the inability to counter the overturning moments will, in many instances, limit the load-handling capability, (4) conventional valve-controlled hydraulic servos are unsuitable for the Man Amplifier, and (5) particularly difficult problems will be encountered in the general areas of mechanical design, sensors and servomechanisms.

CAL is conducting, during the present program, an investigation of the compatibility existing between a human occupant and an exoskeletal structure possessing limited joint degrees of freedom. The ultimate objective of this program is the determination of the feasibility of surrounding the human with a powered exoskeleton in such manner that he is able to perform tasks applicable to a military mission.

This interim report summarizes efforts, during the present contract, to select arrangements of and generate a preliminary design for a non-powered exoskeletal structure representing a reasonable compromise between the need to accommodate the essential joint motions of the human body and the need to produce a device that can be installed on and worn by a human operator.

Section 2 of this report presents conclusions drawn from a search of the applicable literature. In addition, summaries of information from the literature (applicable to the preliminary design of an exoskeletal structure) and conclusions drawn by other investigators are presented in an appendix (see Section 8. 1).

To assess the feasibility of experimentally measuring the paths of instant centers of rotation of human joints, an attempt was made to measure such a path (for the elbow joint) during the present program. Conclusions drawn from the results of these measurements are presented in Section 3. Section 4 presents preliminary designs of three basic exoskeletal joints. Section 5 presents a preliminary design of the exoskeletal structure for the arm complex comprising shoulder, upper arm, elbow, forearm and wrist. Future work planned in the present program is discussed in Section 6.

For the convenience of the reader, a description of skeletal motions, reproduced from Reference 4, is presented in Appendix 8.2.

2. LITERATURE SURVEY

A comprehensive search of available literature was made in the fields of human anatomy, physical anthropology, limb prosthesis and orthopaedic devices. The purpose of this survey was to obtain data for the kinematics of joint motions, including descriptions of the path of instantaneous centers of rotation, maximum angles of rotation and lengths of limb members. A second purpose was to consider mechanisms used in various existing exoskeletal devices.

Two basic conclusions were drawn from the literature survey:

a) The instantaneous centers of rotation of human joints do not remain fixed; rather, the centers shift as functions of relative position between the limbs, thus describing paths of instant centers of rotation. (Reference 1, Reference 14 and Reference 16, pp. 80-89).

b) The great majority of orthopaedic devices use pinned joints (i. e., joints with fixed centers of rotation). Various mechanical devices have been designed in an attempt to simulate the path of instant centers of rotation (Reference 1); however, such devices are rarely used.

If the joints of the exoskeleton are to simulate the kinematics of human joints it is necessary to have complete information on the paths of the instant centers of rotation, (i. e., on the variation of the path as a

function of size of the subject as well as the description of the paths of the instant centers of rotation for one subject). This information was not found in the literature and personal contact with persons currently conducting research on joint motion, orthopaedic devices and prosthetics yielded no additional information.

Sufficient information was found in the literature to specify the ranges of angles of rotation, equivalent link lengths and locations of equivalent (fixed) centers of rotation. (References 2, 3, 6, 9, 11, 13, 14, 19, 21, 23 and 29).

3. EXPERIMENTAL INVESTIGATION OF THE FEASIBILITY OF MEASURING THE PATHS OF INSTANT CENTERS OF ROTATION

In view of the absence of data in the literature specifying paths of the instant centers of rotation, it was concluded that a brief experimental investigation was in order. The purpose of the investigation was to evaluate the feasibility of experimentally measuring the path of the instant center as part of this ONR sponsored program. Thus, one joint was chosen (the elbow) and data were taken to obtain the following:

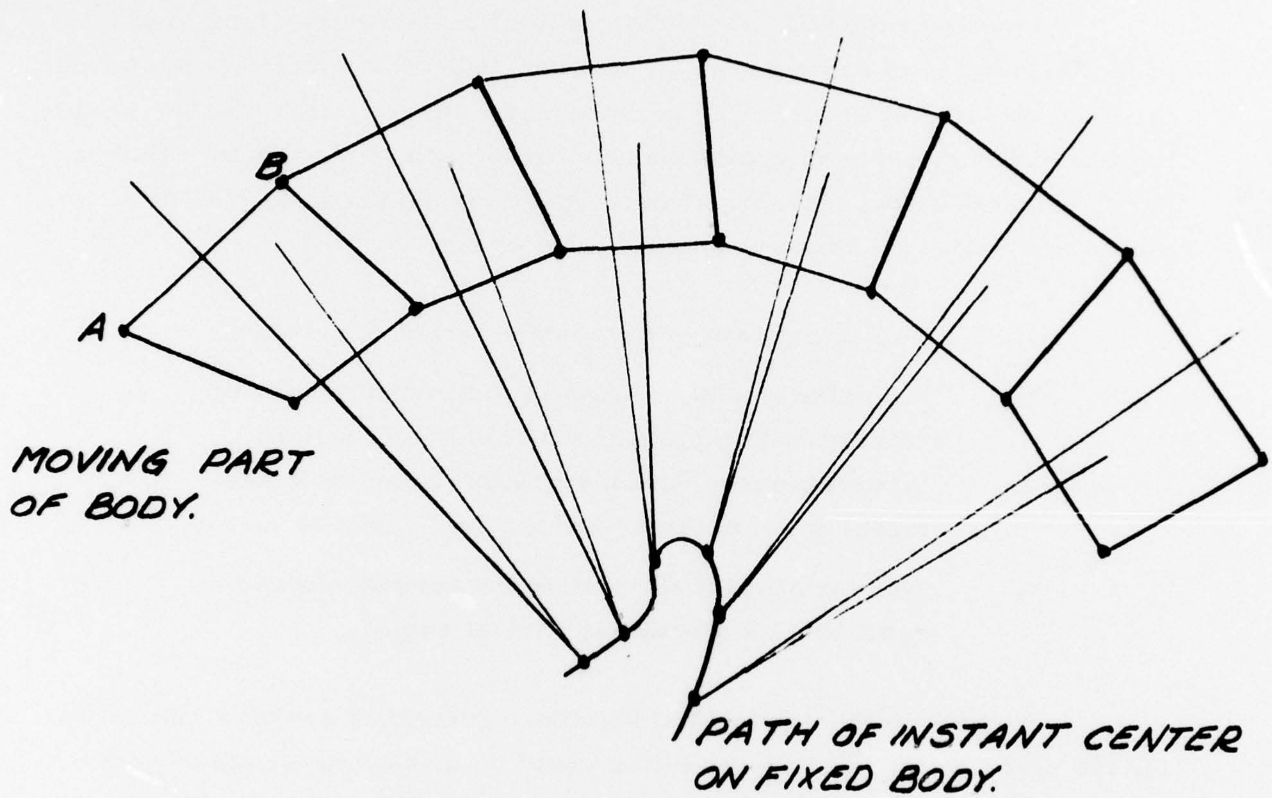
a) The actual path of the instant center of rotation.

b) A comparison of the path of the instant center of rotation with the upper arm held fixed and the forearm moved with the path produced when the forearm is held fixed and the upper arm is moved.

c) The variation of the path of the instant center of rotation as a function of size of subject.

It was hypothesized that if the above quantities could be measured for the elbow joint, similar quantities could be measured for other joints. The method chosen to measure these quantities was developed by Reuleaux, and is used by modern anthropologists to measure kinematic data for joints. (References 14 and 16).

Figure 1 shows the general method developed by Reuleaux. Two points, fixed on the moving body, change their position as the body moves from position A to B. Lines drawn from a point in the first position to the same point in the second position are bisected by perpendicular lines, and location of the instant center of rotation for motion between the two positions is located where the two perpendicular lines meet. The procedure is repeated for various positions and the path of the instant centers of rotation is the line connecting these points.



NOTE:

THIS FIGURE ILLUSTRATES THE REULEAUX METHOD, IT DOES NOT PRESENT ACTUAL DATA ON JOINT MOTION.

METHOD FOR DETERMINING THE PATH OF INSTANT CENTER OF ROTATION

FIGURE 1

The procedure used for the experiment is outlined below:

a) Three subjects were selected, each representing a size group of the population. Their forearm and upper arm were marked, each with two dots a given distance apart.

b) Each subject flexed his elbow to the limits of voluntary motion, first with the upper arm held fixed in space, then with the forearm held fixed in space.

c) Motion pictures were taken for four complete cycles of motion.

d) The resulting film was projected frame by frame and the data transferred to layout paper.

e) The path of the instant center of rotation was constructed by the Reuleaux method.

Unfortunately, the experimental technique was too crude for accurate determination of the instant center of rotation. Graphical analysis of the photographs produced a cluster of instant centers falling within a circle of approximately three inches diameter. This scatter in location is attributed (in part) to stretching of the skin and to the errors inherent in graphical analysis.

The following conclusions were therefore drawn:

a) The method evaluated will not produce data sufficient to describe the path of the instant center of rotation.

b) Many data points are needed because the path of the instant center shifts erratically, instead of describing a smooth curve. (This erratic shift was also found by other experimenters. See, for example, References 14 and 16.) In addition, point locations on the film must be determined with great accuracy because slight errors in point locations cause large errors in the apparent path of the instant center.

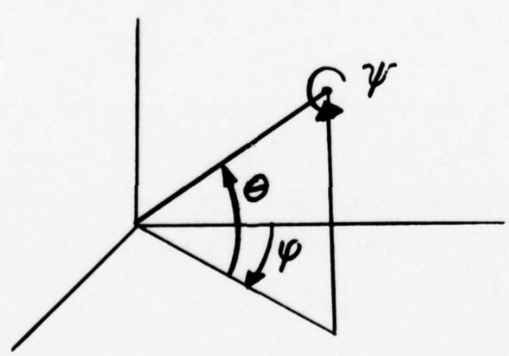
c) An experimental program to determine accurately the path of the instant center requires high speed, large size motion pictures. The data should be analyzed using a numerical rather than a graphical method and many subjects should be measured.

d) It is not feasible to measure the path of the instant center (as described above) for each joint as part of the present investigation.

4. DESIGN OF BASIC EXOSKELETAL JOINTS

The literature survey revealed that nearly all prosthetic and orthopaedic devices use pinned joints. On the other hand, some of these devices have been designed with mechanisms that do allow the instant center of rotation to shift. However, these devices are not widely used, implying that the resulting improvement in simulation of the motion of the joint does not warrant the additional complexity and expense. Further, Sections 2 and 3 of this report point out that data describing the path of the instant center of rotation (e.g., data necessary for simulating the joint motion) are not available. Also, Reference 30 shows that a point fixed relative to a body member moves in a path that deviates only slightly from a circular path. A decision was, therefore, made to use pinned joints in the design of the non-powered exoskeleton.

The approximation of fixed centers of rotation, introduced by selecting pinned joints, limits the motion at any joint to three or fewer degrees of freedom. The degrees of freedom are the three angles of rotation (φ , θ and ψ) shown in Figure 2.



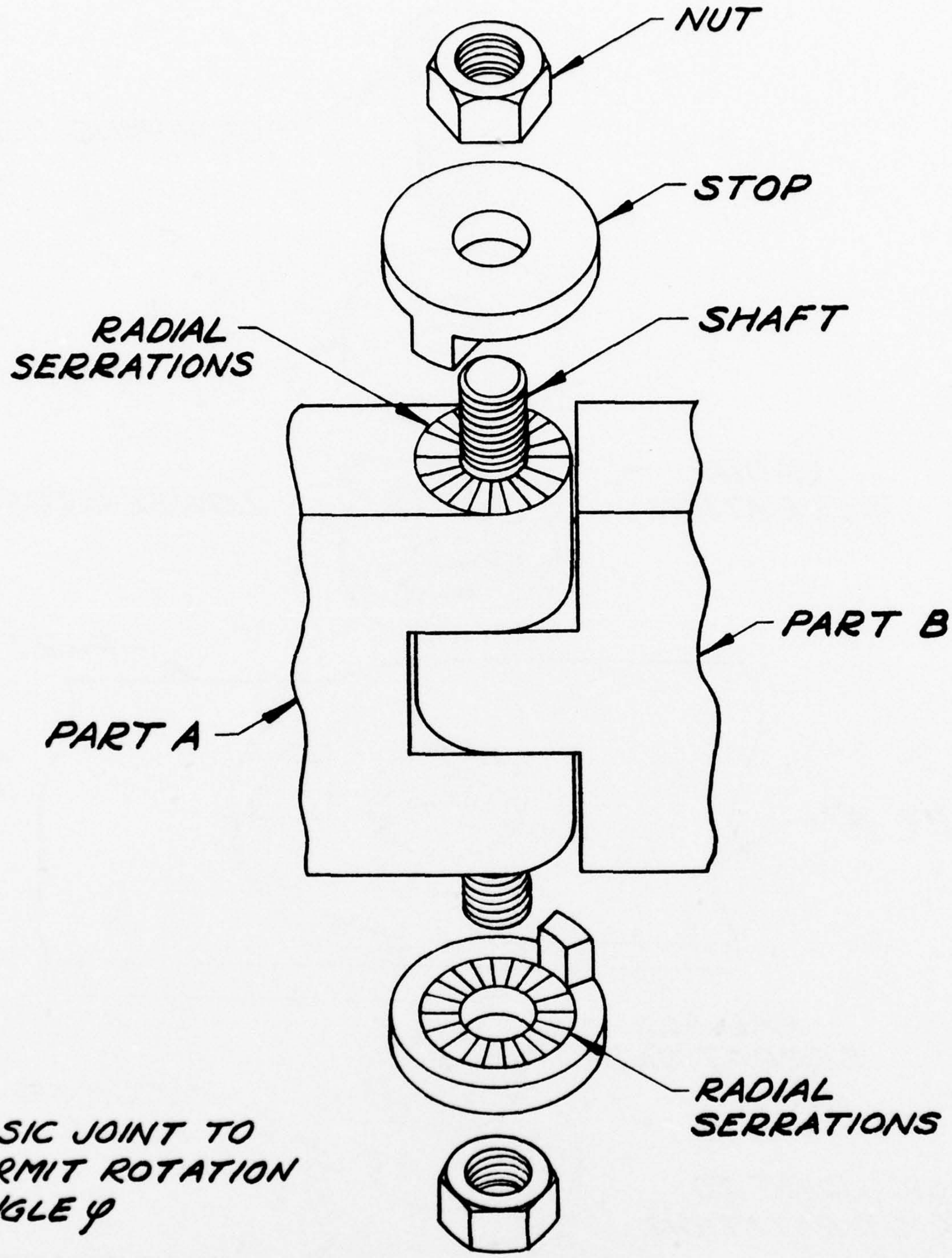
DEGREES OF FREEDOM
FIGURE 2

Rotation through these angles may be produced in the exoskeleton by the mechanisms shown in Figure 3.

The non-powered exoskeleton will be used to determine the minimum number of degrees of freedom required to perform specified tasks. Therefore, the exoskeleton must include mechanisms to limit the rotation in each degree of freedom at each joint. Accordingly, "stops" are included in the basic joints shown in Figures 3A, B and C. The operation and adjustment of the stops shown in Figure 3A can be described as follows. Parts A and B are free to rotate about the shaft. The two outer surfaces of Part A, adjacent to the shaft, are serrated. The stops have mating serrations so that tightening the nuts locks the stops firmly to Part A. Protrusions on the stops limit the motion of Part B relative to Part A. Adjustment of the range of rotation between stops is made by placing the stops in different positions.

The operation of the joint shown in Figure 3B can be described in a similar manner. Part A is free to rotate on the hinge shaft, and the shaft is fixed to Part B. The clamping screw fastens the stops to the shaft, and serrations hold the stops in place. Protrusions on the stops contact a protrusion on Part A, thus limiting the range of rotation. Adjustment of the limits to angular rotation is made by rotating the two stops relative to Part A and reclamping.

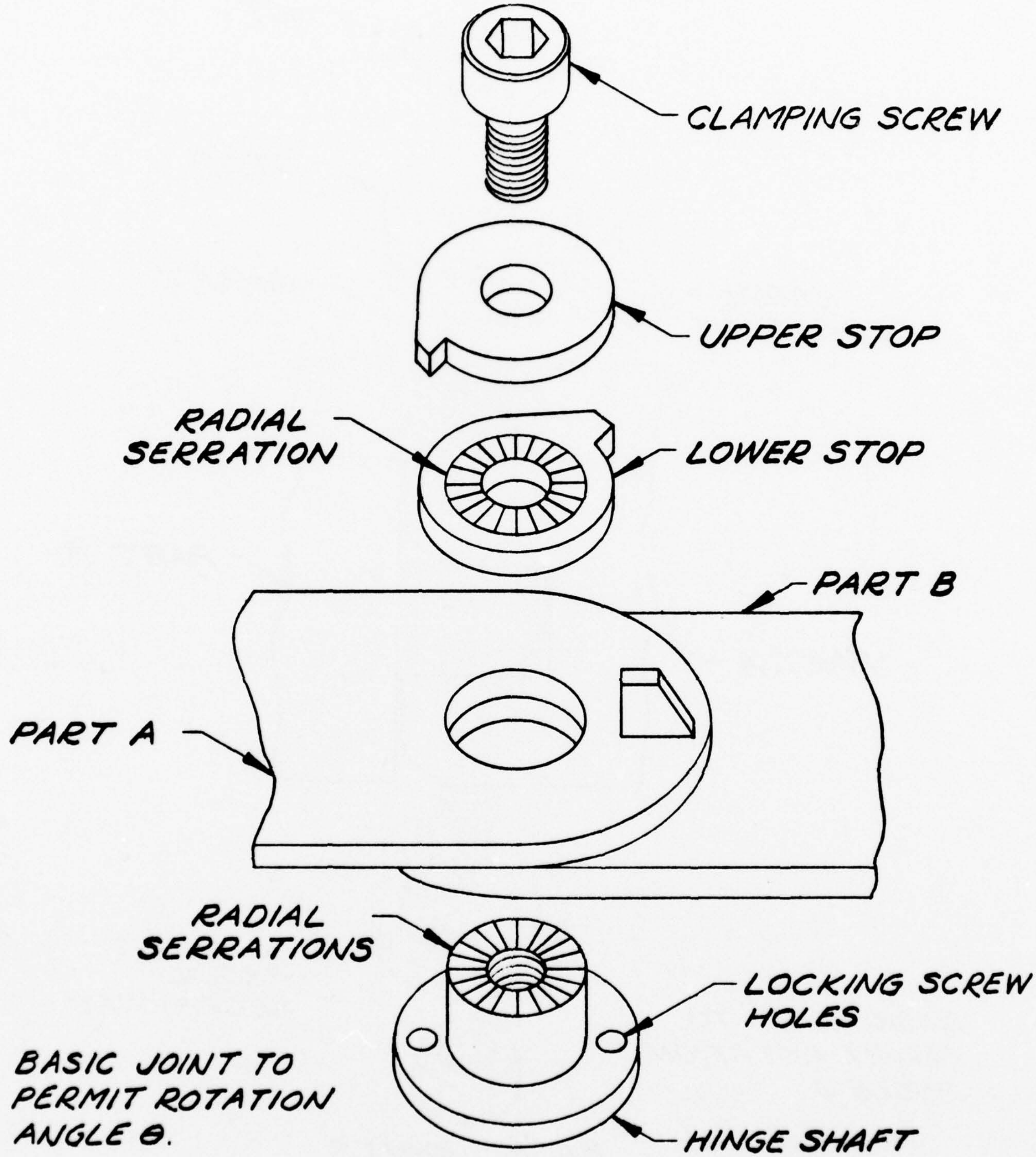
On the basic joint shown in Figure 3C, Parts A and B are sections of cylinders, able to slide relative to each other but held in contact by Part C. Part D, clamped to Part A, limits the movement of Part B. Limits to rotation are modified by changing the position of Part D on Part A.



BASIC JOINT TO PERMIT ROTATION ANGLE φ

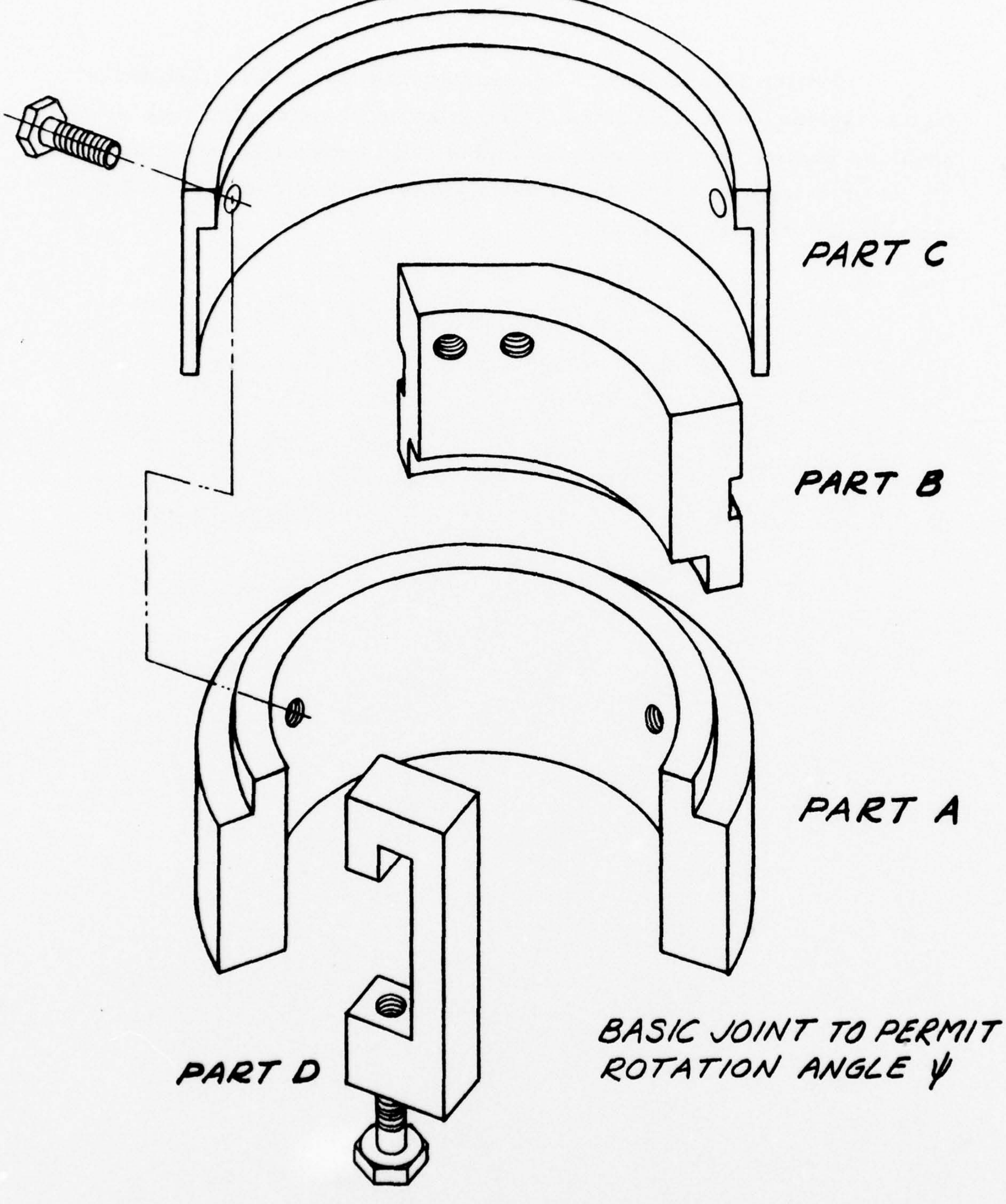
BASIC JOINTS

FIGURE 3A



BASIC JOINTS (CONTINUED)

FIGURE 3B



BASIC JOINTS (CONTINUED)

FIGURE 3C

Section 5 describes an assembly of the above described basic joints, together with rigid links, to form an exoskeletal structure for the shoulder-arm-wrist complex. Assembly of an exoskeletal structure for the lower extremity, using these basic joints, will be considered during the remainder of the program.

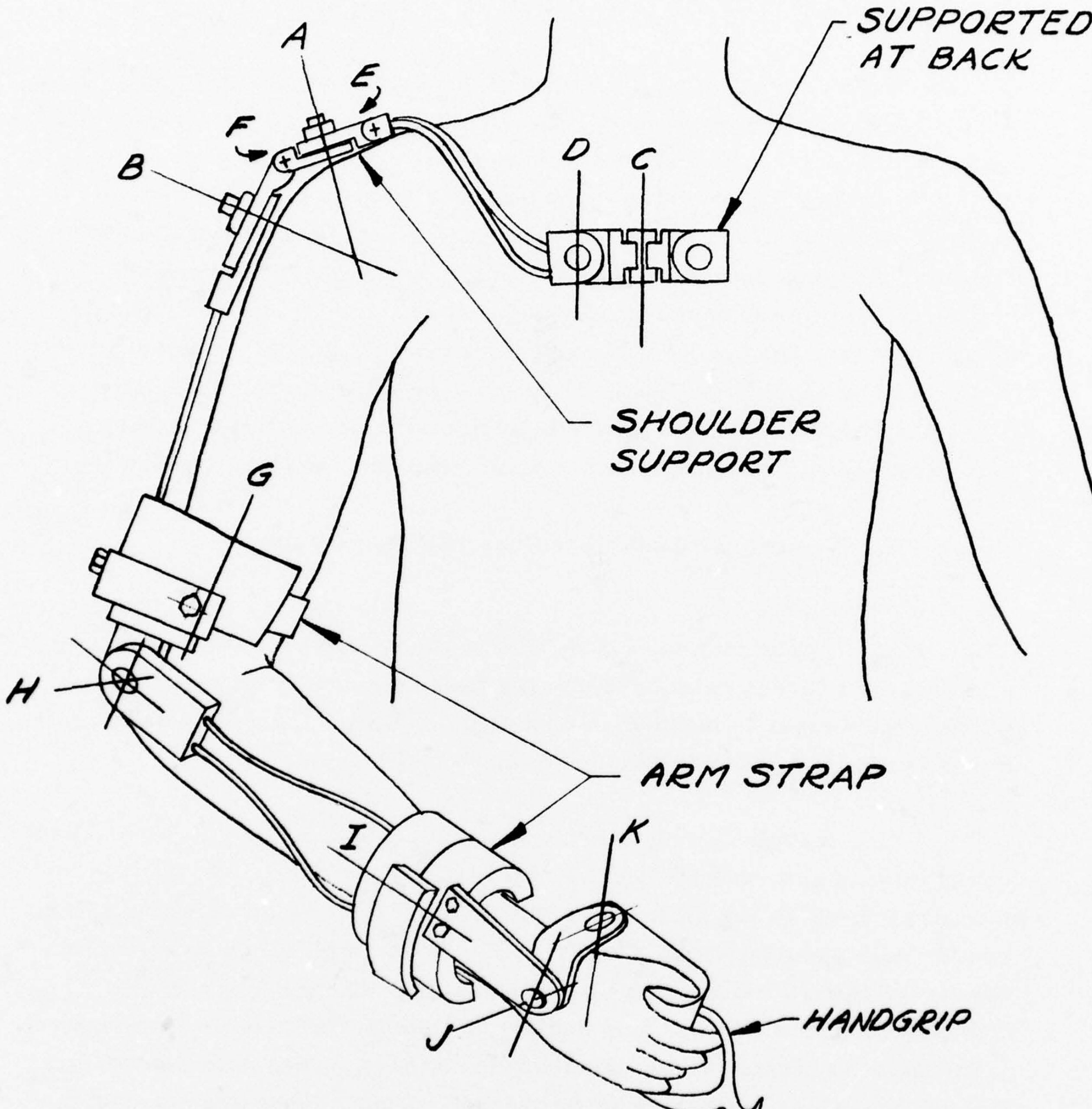
5. PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE FOR THE SHOULDER-ARM-WRIST COMPLEX

Figure 4 presents a preliminary design of an exoskeletal structure for the shoulder-arm-wrist complex. The unit is supported at the wearer's back and shoulder, and is attached to the wearer with two arm straps on each arm. A yoke is provided at the shoulder support to cause the exoskeletal structure to follow the shoulder during flexion and extension of the scapula. The joint located at the back of the wearer, near the spinal column, would be supported by an exoskeletal structure representing the spinal column. The unit shown in Figure 4 can be adjusted to the size of the wearer by varying the length of the links between joints. Each degree of freedom provided at each joint can be limited independently. A handgrip is provided for attachment of various hand devices (hooks, etc.).

5.1 Anatomical Factors Governing Basic Joint Selection

The motion of each joint in the shoulder-arm-wrist complex is discussed below in relationship to the manner in which the exoskeleton permits the wearer to perform normal body motions. Assembly drawings of the exoskeletal joints are included where appropriate.

The scapula is able to be abducted and adducted, and to move up and down from its rest position. These motions, shown in Figure 12(a) and (b), (see Appendix 8.2) are permitted in the exoskeleton by four axes of rotation, two for each shoulder (axes C and D in Figure 4). Reference 30 states that the center of the circular path that approximates this motion is at the intersection of the humeral axis and sagittal plane. Because the exoskeletal joint cannot be located at this point within the body, it has been placed near the sagittal plane, at the back of the wearer. Thus, some relative motion



PRELIMINARY DESIGN OF THE EXOSKELETAL STRUCTURE FOR THE SHOULDER-ARM-WRIST COMPLEX.

FIGURE 4

will occur between the exoskeleton and the shoulder because the exoskeletal joint is not located at the equivalent center of rotation for these scapula motions. However, the relative rotation of the scapula on the thoracic wall is small; thus, the relative motion between the exoskeleton and the body will also be small. A drawing of this exoskeletal joint is shown in Figure 5.

The humerus, or upper arm, is capable of four motions relative to the scapula:

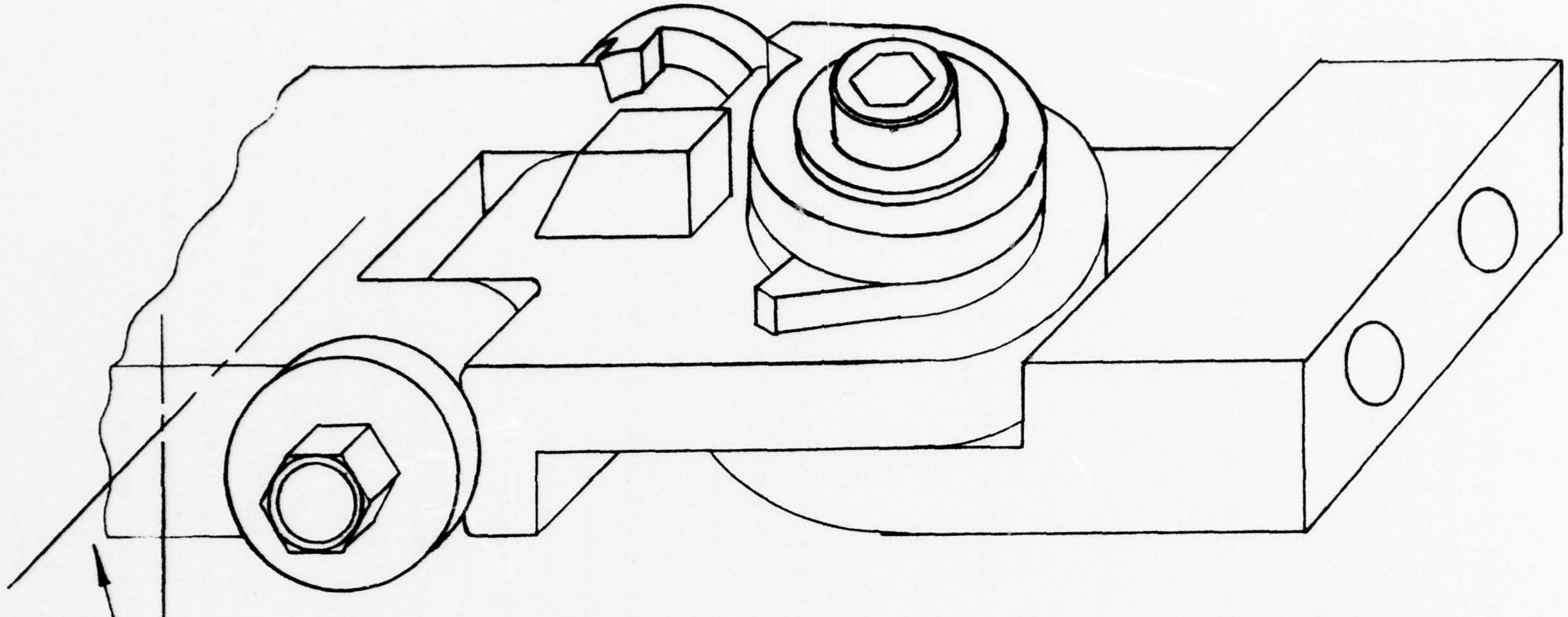
(1) *flexion and extension*

(2) adduction and abduction

(3) medial and lateral rotation and

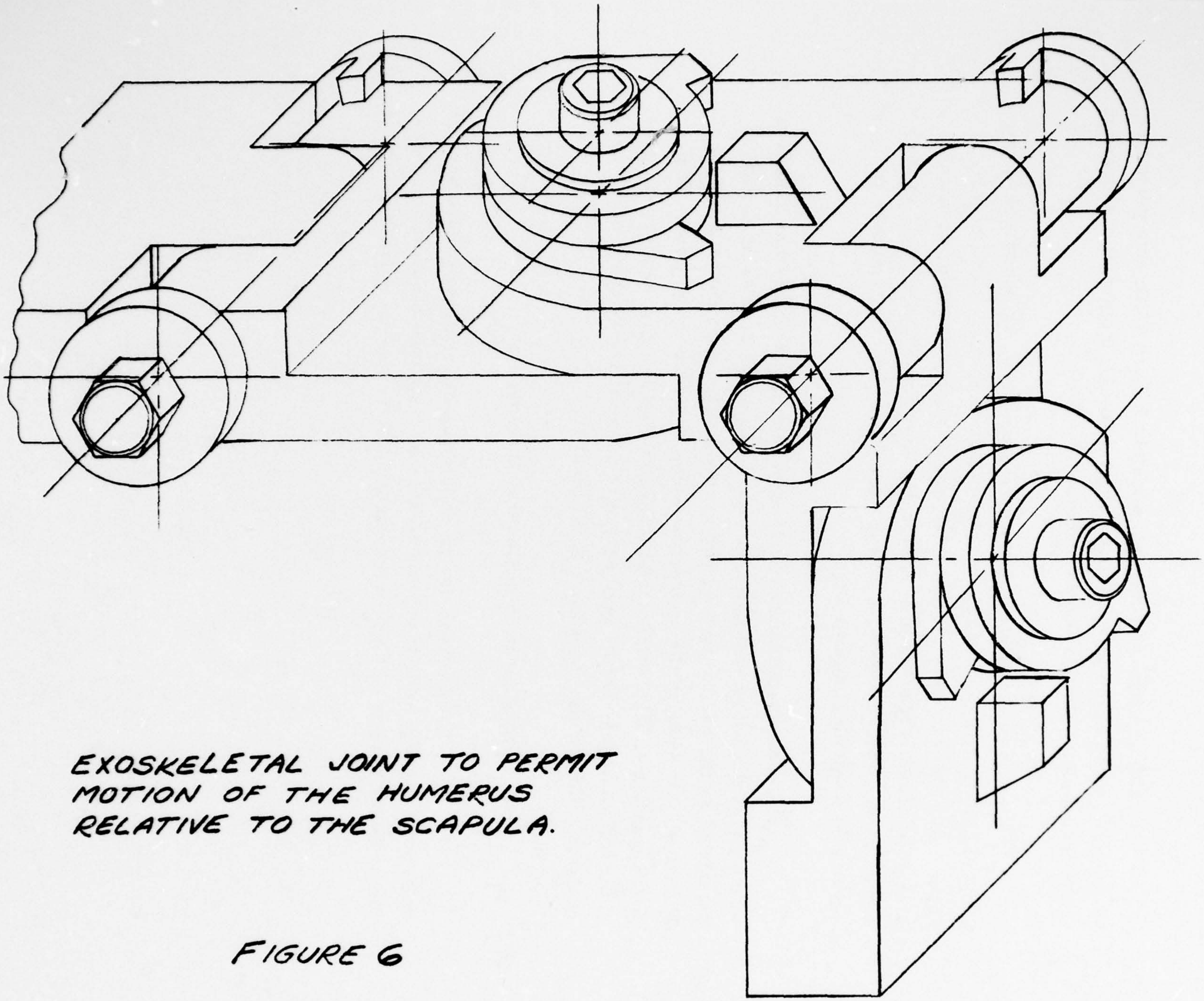
(4) lateral elevation.

These motions are shown in Figure 12(b), (c), (d), (e) and (f). (See Appendix 8.2). Flexion and extension of the shoulder are permitted by the exoskeleton by rotation about an axis beyond the shoulder and passing through the joint between the scapula and the humerus (Axis B, Figure 4). Adduction and abduction of the shoulder are permitted by the exoskeleton by rotation about an axis above the shoulder and passing through the joint between the scapula and the humerus (Axis A, Figure 4). Lateral elevation of the shoulder is permitted by the exoskeleton by rotation about two parallel axes located above the shoulder (Axes E and F, Figure 4). Both of these axes, rather than one axis in front of or behind the shoulder, are used for the following reasons. Any mechanical device in front of the shoulder would prevent the wearer from first elevating and then adducting his arm. Similarly, any mechanical device behind the shoulder would prevent the wearer from first flexing and then abducting his arm. The two parallel axes are not in line with the joint between the scapula and the humerus; however, each axis is independent so that the center of rotation is not fixed but is free to match the motion of the human skeleton. An assembly drawing of the exoskeletal joint is shown in Figure 6.



EXOSKELETAL JOINT TO PERMIT MOTION OF THE SCAPULA RELATIVE TO THE SPINE.

FIGURE 5



EXOSKELETAL JOINT TO PERMIT MOTION OF THE HUMERUS RELATIVE TO THE SCAPULA.

FIGURE 6

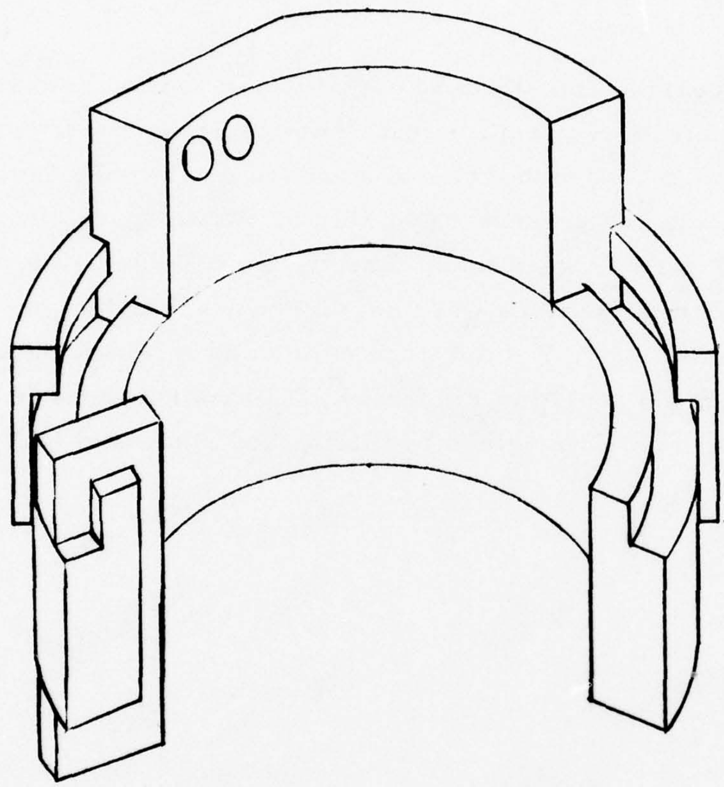
Medial and lateral rotation, shown in Figure 12(f), are permitted by a sleeve between the elbow and shoulder (Axis G, Figure 4). A drawing of this exoskeletal joint is shown in Figure 7.

Flexion of the elbow, shown in Figure 13(b), is permitted by the exoskeleton by using a pinned joint passing through the elbow (Axis H, Figure 4). The exoskeletal joint is shown in Figure 8. Supination and pronation of the elbow (Axis I, Figure 4), shown in Figure 13(c), is permitted by the exoskeleton by a sleeve near the wrist. This sleeve is similar to the joint shown in Figure 7.

Wrist extension and wrist flexion, and ulnar and radial deviation of the wrist are shown in Figure 14 (see Appendix 8.2). Wrist motion is permitted by the exoskeleton by two perpendicular axes (Axes J and K, Figure 4), crossing at the approximate center of the wrist joint. The corresponding exoskeletal joint is shown in Figure 9. A handgrip is provided for attaching "hand" devices and to cause the wrist joint of the exoskeleton to follow the movement of the wearer.

5.2 Specification of General Dimensions

Exoskeleton design requires that locations of (1) approximate joint centers and (2) pertinent external body points be known. Also, the probable ranges of these dimensions must be known in order to specify

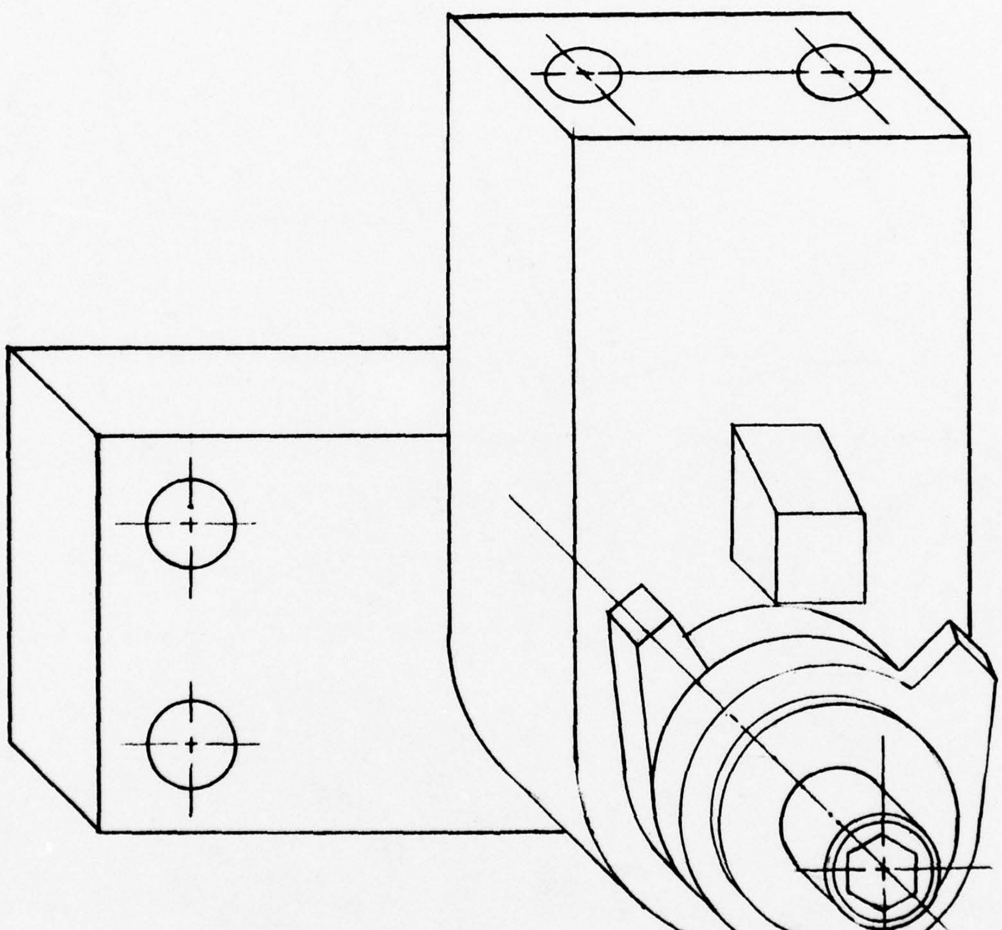


EXOSKELETAL JOINT TO PERMIT
UPPER ARM (HUMERUS) ROTATION

FIGURE 7

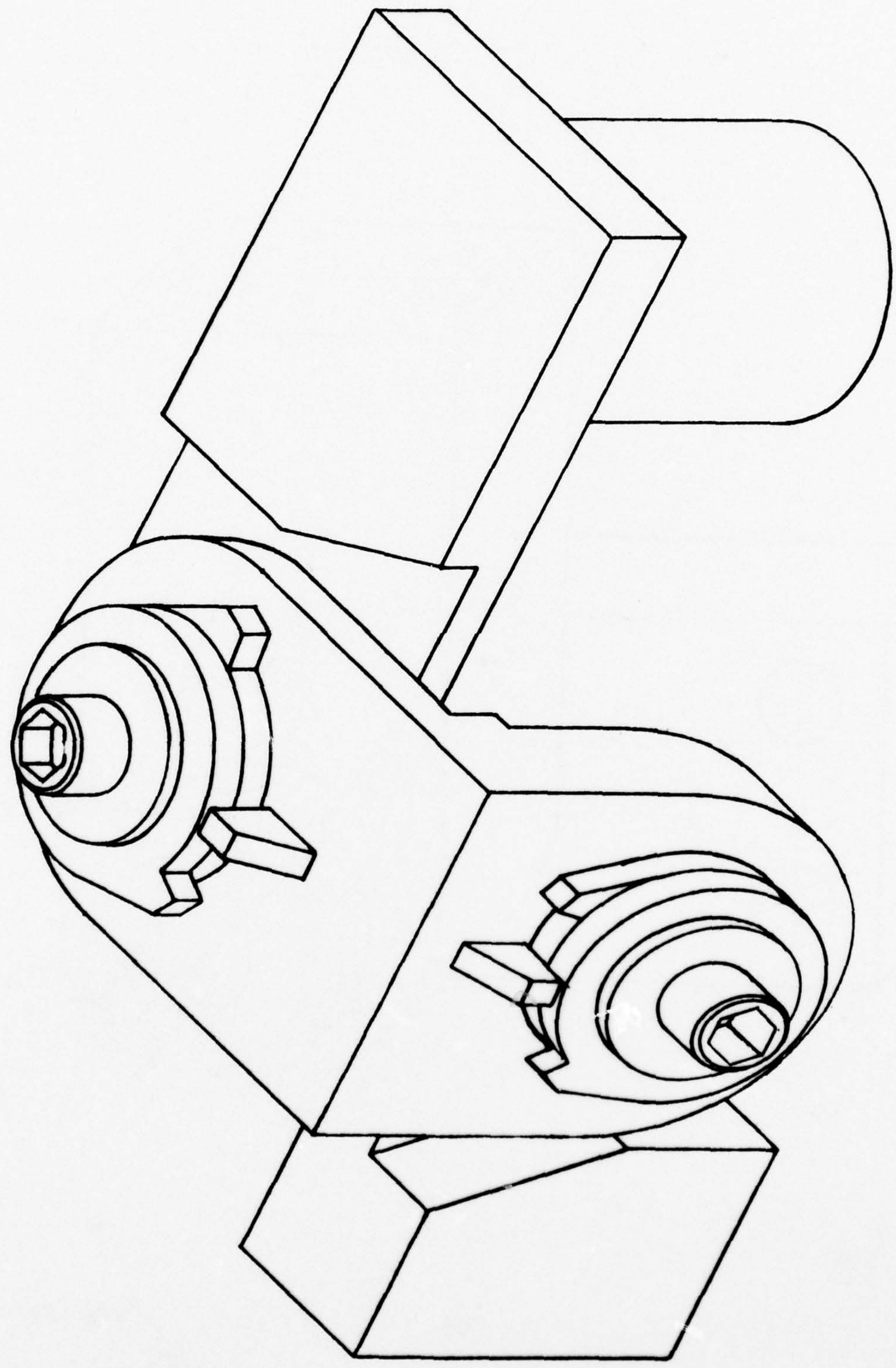
the range of adjustment that should be designed into the exoskeleton. Data that locates approximate joint centers and specifies the pertinent body dimensions (both mean value and range for 90 percent of the adult, male population) are presented in Figure 10. The sources of these data are reviewed below.

Mean values and standard deviations of measurements of the human skeleton, measured from approximate joint centers, are presented in Tables 4, 7 and 8. Mean values and standard deviations of measurements of the human body are presented in Table 6. Where possible, the data presented in Figure 10 were taken directly from Tables 4, 6, 7 and 8. When the desired dimensions were not directly obtainable, mean values taken from Tables 4, 6, 7 and 8 were either added or subtracted to obtain the mean values presented in Figure 10. The indicated range in these dimensions was then determined by the method discussed in Appendix 8.3.



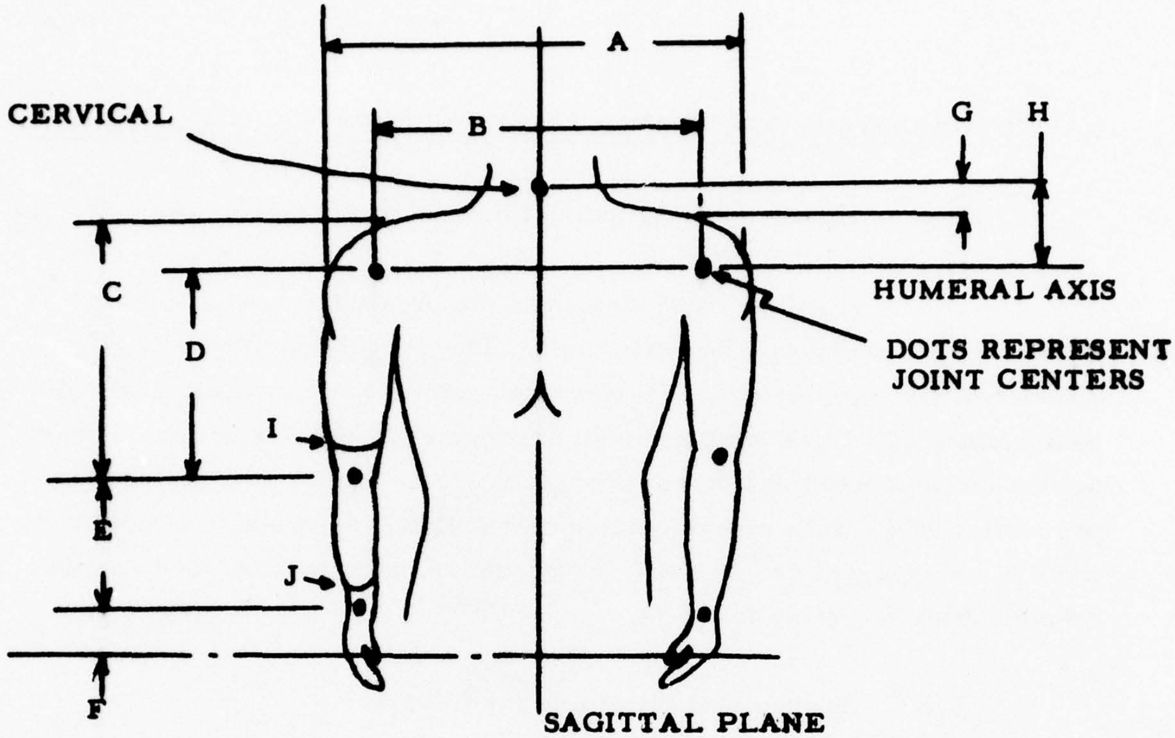
EXOSKELETAL JOINT TO PERMIT FLEXION OF THE ELBOW

FIGURE 8



EXOSKELETAL JOINT TO PERMIT WRIST MOTION

FIGURE 9



DIMENSION		MEAN VALUE INCHES	RANGE - INCHES
A	Shoulder Width - Overall	17.9	16.5 - 19.4
B	Shoulder Width - Joint Center to Joint Center	14.3	13.2 - 15.4
C	Top of Shoulder to Elbow Joint Center	13.0	12.2 - 13.8
D	Shoulder Joint Center to Elbow Joint Center	11.3	10.3 - 12.3
E	Elbow Joint Center to Wrist Joint Center	9.9	9.6 - 10.2
F	Wrist Joint Center to Center of Grip	3.5	3.2 - 3.8
G	Cervical to Top of Shoulder	2.6	2.5 - 2.7
H	Cervical to Shoulder Joint Center	4.2	3.8 - 4.6
I	Upper Arm Girth	10.9	9.7 - 12.1
J	Forearm Girth	10.5	9.5 - 11.5

FIGURE 10 JOINT CENTER AND BODY DIMENSIONS FOR THE EXOSKELETAL SHOULDER-ARM-WRIST COMPLEX

6. FUTURE WORK CONTEMPLATED DURING PRESENT CONTRACT

6.1 Exoskeletal Structure for the Lower Extremity

A preliminary design of the exoskeletal structure for the lower extremity will be performed. The procedure used will be similar to that employed for the shoulder-arm-wrist complex, i.e., the basic joints will be assembled in an arrangement suitable to permit basic human motions used during common activities. Where the kinematic properties of a joint are so complex that it is not possible to simulate the motion with single axes of rotation, redundant axes will be used, as was employed for the shoulder joint.

6.2 Exoskeletal Structure for the Spine

A preliminary design will be made for the exoskeletal structure joining the lower extremity and the shoulder-arm-wrist complex. The design of an exoskeletal spine is anticipated as an area requiring considerable effort since a different type of joint arrangement is required than is used for the shoulder and lower extremity complexes.

6.3 Structural Analysis of the Exoskeleton

The non-powered exoskeleton is not intended to resist large forces. However, if the rotation at a particular joint is limited the exoskeletal structure must be sufficiently rigid so that structural deflections do not permit equivalent rotations. Therefore, the necessary strength and rigidity of the exoskeletal structure will be analyzed to determine reasonable requirements for the section modulus of the rigid links.

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27. Provins, K. A. and Salter, N., Maximum Torque Exerted About the Elbow Joint, Journal of Applied Physiology, Vol. 7, No. 4, January 1955.

28. Radcliffe, C. W., Prosthelic Mechanisms for Leg Amputees, Proceedings from the Sixth Conference in Mechanisms, October 10-11, 1960.

29. Roberts, D. F., Provins, K. A., and Morton, R. J., Arm Strength and Body Dimensions, Human Biology, Vol. 31, No. 4, December 1959.

30. Taylor, C. L., Blaschke, A. C., A Method for Kinematic Analysis of Motions of the Shoulder, Arm and Hand Complex, Annals of the New York Academy of Sciences, 51:7, pp 1251-1265, January 1951.

31. Tomvic, R. and Boni, G., An Adaptive Artificial Hand, IRE Transactions on Automotive Control, April 1962.

8. APPENDICES

8.1 SUMMARIES OF REFERENCES APPLICABLE TO THE PRELIMINARY DESIGN OF THE EXOSKELETON

A comprehensive search of available, applicable literature in such fields as human anatomy, physical anthropology, limb prosthesis and orthotic devices was made. The purpose of this literature search was to procure data on ranges of joint motions and simulation of joint motions. References pertinent to the preliminary design of a non-powered exo-skeletal structure are briefly discussed and applicable data contained therein are presented. Papers preceded by an asterisk (*) are outlined in, "Annotated Bibliography of Applied Physical Anthropology in Human Engineering" by Hansen, Yoh and Hertzberg.

8.1.1

Alldredge, R. H., and Snow, B. M., Lower Extremity Braces, Orthopaedic Appliances Atlas, Vol. 1, pp 345-438, J. W. Edwards, Ann Arbor, Michigan, 1952.

An historical review of orthotic Devices for the Lower Extremity is included in this paper. The review discusses work done since the early 19th century, and thirty-five figures of braces and splints, used during the 19th and early part of the 20th centuries, are shown. The early braces and splints shown in the figures are remarkably similar to devices now being used. The devices are pin-jointed, where motion is permitted, and are attached to the body with leather straps.

The anatomy of the lower extremity is discussed and the motion at each joint is analyzed. It is observed that joint motion is not the same as pin-jointed motion, but the degree that the center of rotation shifts is not discussed. Also, nearly all motion of the braces and splints use pin-jointed mechanisms. An exception is the knee joint. Three of the mechanisms shown permit the instant center of rotation to shift these mechanisms along a path, include 1) a four-bar mechanism, called the Schede-Haberman joint, 2) a geared mechanism, called the Hanger polycentric knee joint, and 3) a double-pivot joint (which does not fix the instant center at a point, but allows it to float in order to match the knee motion) designed by Snow and Hauser.

This reference concludes with a detailed discussion on practices used in construction and design of splints and braces, and on acceptable methods of attaching them to the body.

8. 1. 2

*Ashe, W. F., Bodenman, P., Roberts, L. B., Anthropometric Measurements, Project No. 9, File No. 741-3, Armored Force Medical Research Laboratory, Fort Knox, Kentucky, 1 February 1943.

Basic anthropometric measurements made on soldiers in the Armed-Forces School are compared with measurements made on Air Force personnel. It is shown that there is no statistically significant difference between measurements of the two groups.

8.1.3

Barter, J. T., Emanuel, I., Truett, B., A Statistical Evaluation of Joint Range Data, WADC Technical Note 57-311, ASTIA Document No. AD 131028, Wright-Patterson Air Force Base, Ohio, August 1957.

Data on motions of joints presented by W. T. Dempster in Space Requirements of the Seated Operator, are analyzed statistically to convert them to a form more applicable to Air Force Design Problems. Mean values and standard deviations for the maximum ranges of rotation at various joints are presented in Table 1.

The sample size used to obtain these data was 39. However, the data were compared with Air Force data from over 4000 subjects. It was found that the mean values were nearly the same, and that the standard deviation was somewhat larger than the standard deviation obtained from the Air Force data.

8.1.4

*Batch, J. W., Measurements and Recordings of Joint Function, United States Armed Forces Medical Journal, Vol. 6, No. 3, pp 359-382, March 1955.

Possible movements of the human skeleton are defined and a method for recording joint motion (Cane and Roberts, Method for Measuring and Recording Joint Function) is discussed in detail. Definitions of skeletal motions, taken from this paper, are shown in Section 8.2.

TABLE 1

RANGES OF JOINT MOTION

Joint & Type of Movement	Mean Value Degrees	Standard Deviation Degrees
Wrist		
Flexion	90	12
Extension	99	13
Total	189	21
Abduction	27	9
Adduction	47	7
Total	74	13
Forearm		
Supination	113	22
Pronation	77	24
Total	190	30
Elbow		
Flexion	142	10
Shoulder		
Flexion	188	12
Extension	61	14
Total	249	19
Abduction	134	17
Adduction	48	9
Total	82	20
Medial Rotation	97	22
Lateral Rotation	34	13
Total	131	24

TABLE 1 (Continued)

Joint & Type of Movement	Mean Value Degrees	Standard Deviation Degrees
Hip		
Flexion	113	13
Abduction	53	12
Adduction	31	12
Total	84	14
Medial Rotation - Prone	39	10
Lateral Rotation - Prone	34	10
Total	73	16
Medial Rotation - Sitting	31	9
Lateral Rotation - Sitting	30	9
Total	61	14
Knee		
Voluntary Flexion - Prone	125	10
Forced Flexion - Prone	144	9
Voluntary Flexion - Standing	113	13
Forced Flexion - Kneeling	159	9
Medial Rotation - Sitting	35	12
Lateral Rotation - Sitting	43	12
Total	78	16
Ankle		
Flexion	35	7
Extension	38	12
Total	73	14
Foot		
Inversion	24	9
Eversion	23	7
Total	47	13

Data taken from A Statistical Evaluation of Joint Range Data by James T. Barter, Irvin Emanuel, and Bruce Truett.

The range of motions shown in this report are considered by the authors to be the average values. It is mentioned that the ranges given may vary slightly from other published data because each movement of each joint is given, rather than the gross movement produced by motion at several joints.

8.1.5

*Blaschke, A. C. and Taylor, C. L., The Mechanical Design of Muscle-Operated Arm Prostheses, Journal of The Franklin Institute, Vol. 256, pp 435-458, 1953.

The use of human muscles to control prosthetic devices, a process called cineplastic, is discussed in this reference. Cineplasticy is achieved by inserting a control cable through a tunnel and into a muscle, and connecting the cable to the artificial limb. Thus, if the forearm is missing, the bicep can be used to cineplastically control an artificial hand, or hook.

A hook, operated as discussed above, is analyzed to determine the required motion and force to perform given tasks. Several lever mechanisms for translating muscle work to work at the prosthetic hook are discussed.

8.1.6

Catranis, J. G., Some Recent Developments in Lower Extremity Prostheses, Annals of the New York Academy of Sciences, 51:7, pp 1229-1250, January 1951.

The basic functional requirements of lower extremity prostheses are discussed and motion of the leg during normal walking is described in detail. Because the designs of the prosthetic legs shown are based upon the functional requirements of the device, and not upon simulating actual limb motion, these designs cannot be used directly for preliminary design of the exoskeletal structure.

Table 2 contains data taken from graphs appearing in this report. The values shown are maximum values encountered during the motion cycle.

TABLE 2

MAXIMUM ROTATION OF HIP, KNEE, AND ANKLE JOINTS DURING WALKING AND DESCENDING STAIRS

Motion Cycle	Joint	Maximum Rotation From Rest Degrees	
Straight Walking	Femur-Pelvis (Hip)	+ 29	-12
	Tibia-Femur (Knee)	+ 66	0
	Tarsals-Tibia (Ankle)	+ 12	-18
Descending Stairs	Tibia-Femur (Knee)	+ 100	+20
	Tarsals-Tibia (Ankle)	+ 42	-19

Data taken from Some Recent Developments in Lower Extremity Prostheses by John G. Catranis.

8.1.7

Daniels, G. S., The "Average Man"?, Technical Note WCRD 53-7, RDO No. 695-71, Wright Air Development Center, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio, December 1952.

A sample of 4063 men were examined for physical size to determine how many had average dimensions (average being defined as the middle 30 percent of the total population). The not-average group was eliminated after each measurement, and after 10 measurements there was not a single individual remaining who fell within the average range for all measurements.

8.1.8

*Darcus, H. D. and Salter, N., The Amplitude of Pronation and Supination with the Elbow Flexed to a Right Angle, Journal of Anatomy, Vol. 87, Part 2, April 1953.

Measurements were made on 650 subjects to determine the mean amplitude of pronation and of supination. Data from this report is presented in Table 3.

The following conclusions were drawn in this report:

a. No significant association between either age, sex or previous injury and amplitude of pronation and supination was found.

b. Although differences were found between the mean amplitudes measured on the right and left sides, these differences in the mean values usually were not statistically significant.

c. Wide variation occurred between readings taken successively on the same day and from day to day. It was suggested that this difference was caused by (1) alterations of activity in the antagonist muscles which affected the arc through which the joint was moved, (2) variation in the sensitivity of the stretch receptors, and (3) variations in motivation of the subject.

TABLE 3

FOREARM PRONATION AND SUPINATION

Motion	Mean Amplitude Degrees	Range Degrees	Standard Deviation Degrees
Right-Hand Pronation	63	49-84	10.5
Right-Hand Supination	102	86-122	11.1
Left Hand Pronation	62	49-75	8.6
Left Hand Supination	106	90-121	10.0

Data taken from The Amplitude of Pronation and Supination with the Elbow Flexed to a Right Angle by Darcus and Salter.

8.1.9

Dempster, W. T., Space Requirements of the Seated Operator, WADC Technical Report 55-159, Wright Air Development Center, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio, July 1955.

"The structure of the limb joints and the range and type of their motions were studied on cadaver material, with supplementary work on living subjects, in order to clarify geometric, kinematic and engineering aspects of the limb mechanism. Plans for the construction of manikin joints which showed normal ranges of limb movement were developed from this information. Specifications were also worked out for drafting board manikins which show correct limb ranges for seated postures. Subjects comparable to the model physique of Air Force flying personnel and highly selected small samples of muscular, thin, and rotund builds supplied information on the range of possible hand and foot movements which was consistent with the seated posture. Maximum dimensions of the work space for seated individuals were determined;

a study of the kinematic factors involved permitted an evaluation of the potential utility of different regions within reach. Eight cadavers were dismembered to provide data on such physical constants as mass of parts, segment centers of gravity, density and moments of inertia. This work was supplemented by data on the distribution of body bulk in the living subjects studied. Applications of the above information to analyses of horizontal push and pull forces in terms of couples permitted an evaluation of the effectiveness of body mass, leverages and support areas."*

This paper contains considerable discussion about the kinematic aspects of the extremity joints. The axis of rotation, or instant center, for each joint system is discussed and the shift of this axis of rotation during joint movement is mentioned. However, definitive numerical data describing the amount of this shift is not included.

Table 4 shows dimensions of a three-dimensional linkage assembly that represents the human skeleton.

TABLE 4

SKELETON LINK DIMENSIONS

	Dimension-Inches		
Link	5 Percentile	50 Percentile	95 Percentile
Oavicle	5.16	5.55	5.98
Scapula		1.38	
Humerus	11.26	11.89	12.60
Radius	10.12	10.71	11.22
Half Pelvic	3.13	3.37	3.76
Femur	15.95	17.09	18.11
Tibial	14.96	16.10	17.28

Data taken from Space Requirements of the Seated Operator by Dempster, and converted from centimeters to inches.

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* This summary is quoted directly from the reference.

8.1.10

Dempster, W. T., Free-Body Diagrams as an Approach to the Mechanics of Human Posture and Motion, contained in Biomechanical Studies of the Musculo-Skeletal System by Evans, et al, Copyright 1961 by Charles C. Thomas, Publisher, Springfield, Illinois.

Methods of applying mechanics to the study of human skeletons are discussed. The maximum force a human is capable of exerting is related to the forces and moments at each joint.

8.1.11

Dempster, W. T., The Anthropometry of Body Action, WADD Technical Report 60-18, Aerospace Medical Laboratory, Wright Air Development Command, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio.

Joint motion, methods of determining range of joint movement and location, or path, of instant centers of rotation are discussed, but no data on the path of instant centers is presented. It is concluded that the path of instant centers of rotation is random in nature, forming a cluster of points rather than a fixed path. Further, it is shown that with the forearm restrained and the wrist moved in flexion-extension a given cluster of instant center points exists; whereas, if the hand is restrained and the forearm moved, a different cluster of points exists.

The diameter of the smallest circles that enclose the cluster was found to be three-quarters inch at the shoulder, one-half inch at the elbow and three-quarters inch at the wrist.

8.1.12

Glanville, A. D., and Kreezer, G., The Maximum Amplitude and Velocity of Joint Movements in Normal Male Human Adults, Human Biology, 9:197-211, 1937.

Range of joint motion was measured by using a pendulum device strapped to the subject. The pendulum remained vertical, because of the effect of gravity, and a scale mounted behind the pendulum recorded the angular motion. Results obtained with this device are shown in Table 5.

TABLE 5

AMPLITUDE OF VOLUNTARY MOVEMENT

Joint	Movement	Side	Amplitude* Degrees	Standard Deviation
Shoulder	Flexion	R	179.0	7.2
		L	179.9	6.3
	Extension	R	55.2	10.1
		L	60.0	12.4
	Abduction	R	129.3	11.7
		L	130.3	11.2
	Internal Rotation	R	94.1	22.1
		L	100.0	16.3
	External Rotation	R	82.7	10.0
		L	83.5	16.2
Elbow	Flexion	R	132.3	8.5
		L	144.2	8.9
	Pronation	R	91.1	25.8
		L	93.0	20.7
	Supination	R	99.4	11.0
		L	100.6	10.8

TABLE 5 (Continued)

Joint	Movement	Side	Amplitude* Degrees	Standard Deviation
Wrist	Flexion	R	95.0	10.6
		L	90.0	9.8
	Extension	R	54.1	15.2
		L	65.7	12.6
	Abduction	R	27.1	7.1
		L	31.1	8.4
	Adduction	R	66.1	8.1
		L	66.1	8.8
Hip	Flexion	R	97.8	17.0
		L	105.6	8.3
	Extension	R	48.4	12.9
		L	42.4	9.9
	Abduction	R	70.1	17.0
		L	71.7	14.1
	Internal Rotation	R	60.6	15.2
		L	66.3	13.5
	External Rotation	R	37.0	6.6
		L	30.4	8.3
Knee	Flexion	R	126.6	6.7
		L	123.7	6.7
Ankle	Plantar Flexion	R	28.2	7.4
		L	26.2	8.9
	Dorsiflexion	R	36.8	6.6
		L	39.5	8.3

* Amplitude shown is arithmetic mean of data.

Data taken from The Maximum Amplitude and Velocity of Joint Movements in Normal Male Human Adults by Glanville and Kreezer.

8.1.13

* Hertzberg, H.T.E., Daniels, G.S. and Churchill, E., Anthropometry of Flying Personnel - 1950, WADC Technical Report 52-321, United States Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, September 1954.

Dimensions for 132 body measurements of over 4000 Air Force flying personnel are presented. Data applicable to the design of the exoskeleton are reproduced in Table 6.

TABLE 6

BODY MEASUREMENTS

Measurement (See Figures)	Range Inches	Inches	Standard Deviation Inches
Stature	59.45 - 77.56	69.11	2.44
Shoulder Height*	47.24 - 64.17	56.50	2.28
Elbow Height	36.61 - 49.21	43.5	1.77
Waist Height	34.65 - 48.82	42.02	1.81
Wrist Height	27.56 - 39.76	33.52	1.54
Kneecap Height	15.75 - 23.23	20.22	1.03
Shoulder - Elbow	11.42 - 18.11	14.32	0.69
Forearm - Hand	15.35 - 22.05	18.86	0.81
Hip Breadth - Sitting	11.42 - 18.11	13.97	0.87
Shoulder Breadth	14.57 - 22.83	17.88	0.91
Chest Breadth	9.45 - 15.35	12.03	0.80
Waist Breadth	7.87 - 15.35	10.66	0.94
Hip Breadth	8.27 - 15.75	13.17	0.73
Chest Depth	6.69 - 12.99	9.06	0.75
Waist Depth	5.51 - 11.81	7.94	0.88
Lower Thigh Circumference	14.75 - 28.74	22.39	1.74
Calf Circumference	9.84 - 18.56	14.40	0.96
Ankle Circumference	7.09 - 12.99	8.93	0.57
Biceps Circumference - Flexed	8.27 - 16.93	12.79	1.07
Lower Arm Circumference - Flexed	8.66 - 15.35	11.50	0.73

* Height measurements are measured from the floor with the subject standing erect, but not at forced attention.

Data taken from Anthropometry of Flying Personnel - 1950 by Hertzberg, Daniels and Churchill.

8.1.14

*Lay, W. E. and Fisher, L. C., Riding Comfort and Cushions, Society of Automotive Engineers Journal (Transactions), Vol. 47, No. 5, pp 482-496, 1940.

This paper, in addition to discussing automobile seats, presents anthropometric data taken by army surgeons seventy years ago. These data, showing the location of various hinge points of the human skeleton, are presented in Table 7.

TABLE 7

LOCATION OF HINGE POINTS OF THE HUMAN SKELETON

Hinge	Location* Y	Inches Z
Base of Skull on Spine	0.0	61.58
Shoulder Joint	±7.16	54.78
Elbow	±7.16	41.99
Wrist	±7.16	31.19
Hip	±3.40	35.19
Knee	±3.40	19.19
Ankle	±3.40	2.6

* "Y" represents distance from the spinal column, or sagittal plane, towards the subject's side.

"Z" represents vertical distance from the floor, with the subject standing.

Data taken from Riding Comfort and Cushions by Lay and Fisher.

8.1.15

Roberts, D. F., Provins, K. A. and Morton, R. J., Arm Strength and Body Dimensions, Human Biology, Vol. 31, No. 4, December 1959.

Body size and limb dimensions are correlated with arm strength. Conclusions reached were: (1) persons who tend to be large in one body dimension tend to be above average in all body dimensions as well as in limb strength, (2) longitudinal measurements correlate better with one another than with girth measurements, and conversely. Therefore, there is a fundamental distinction between longitudinal and circumferential aspects of body size.

Data on body measurements are presented in Table 8, and correlation coefficients for anthropometric measurements are presented in Table 9.

TABLE 8

MEANS AND STANDARD DEVIATIONS OF BODY MEASUREMENTS

Measurement	Mean, Inches	Standard Deviation, Inches
Stature	68.19	2.55
Upper Arm Length	12.95	0.87
Forearm Length	10.12	0.52
Hand Length	7.72	0.33
Upper Arm Girth	10.94	0.80
Forearm Girth	10.51	0.51

Stature - Height to vertex, subject standing erect, not at forced attention.

Upper Arm Length - Acromion to upper margin of head of radius, arm hanging straight and muscles relaxed.

Forearm Length - Upper margin of head of radius to tip of styloid of radius.

Hand Length - Tip of styloid process of radius to tip of middle finger, hand flat on a table.

Upper Arm Girth - Midway between acromion and point of elbow, muscles relaxed.

Forearm Girth - Maximum girth, arm hanging loose, muscles relaxed.

Data taken from <u>Arm Strength and Body Dimensions</u> by Roberts, Provins and Morton and converted from centimeters to inches.

TABLE 9

CORRELATION COEFFICIENTS OF ANTHROPOMETRIC MEASUREMENTS

Measurement	a	b	c	d	e	f
a) Stature	-					
b) Upper Arm Length	0.75	-				
c) Forearm Length	0.68	0.35	-			
d) Hand Length	0.73	0.51	0.77	-		
e) Upper Arm Girth	-0.19	-0.10	-0.06	-0.02	-	
f) Forearm Girth	0.26	0.16	0.22	0.39	0.70	-

Data taken from <u>Arm Strength and Body Dimensions</u> by Roberts, Provins and Morton.

8.1.16

Taylor, C. L. and Blaschke, A. C., A Method for Kinematic Analysis of Motions of the Shoulder, Arm and Hand Complex, Annals of the New York Academy of Sciences, 51:7, pp 1251-1265, January 1951.

A method for analyzing skeletal motion is developed. This method comprises the following six steps:

a) measure and calibrate the subject,

b) mark the subject with reference points,

c) photograph the subject performing activities,

d) obtain the Cartesian coordinates of the reference points from the film and correct for parallax,

e) analyze the data to determine axes and angles of the idealized kinematic system and,

f) determine angular velocities and accelerations from serial frames.

The human skeleton is idealized by considering it a four-lever mechanism, rotating on four centers through a total of nine angles. Plots of the path of the centers are shown and are approximated by segments of circles. The error introduced by approximating the path by circular segments is not discussed; however, the data points lie very near the circular line segments.

8.2 DEFINITIONS OF SKELETAL MOTIONS

Detailed descriptions of skeletal motion are included in this report to permit discussion of methods that are used to simulate these motions with the exoskeleton. The descriptions and definitions were taken directly from, Measurements and Recordings of Joint Function by J. W. Batch.

Spine

"The neutral position for the spine is with the patient standing erect evenly on both feet; with knees straight; hips, pelvis, and shoulders level: abdomen in; chest out; pelvis rotated in under vertebral column; chin in; head up, with a perpendicular line of weight bearing passing through the mastoid process across the greater trochanter and tibial tuberosity to the base of the fifth metatarsal. The lumbar and dorsal portions of the spine are practically flat, although the curves can be identified. There is no marked lateral curvature although, normally, there may be a slight lateral curvature with the convexity to the right. The Achilles tendons are perpendicular to the ground.

"Movements. From the neutral position, motions of the spine are flexion, hyperextension, lateral bending to the right and left, rotation to the right and left (Figure 11) and circumduction. These motions are a result of the sum of motions which take place at the articulations between each of the vertebrae in the sagittal, coronal, and transverse planes respectively. Because of this, accurate measurement is difficult. Motions should be compared with the normal for the individual person, considering age and habits. Alterations in the lumbar and dorsal curves should be noted in both the postero-anterior and lateral planes to determine flattening or reversal of these curves.

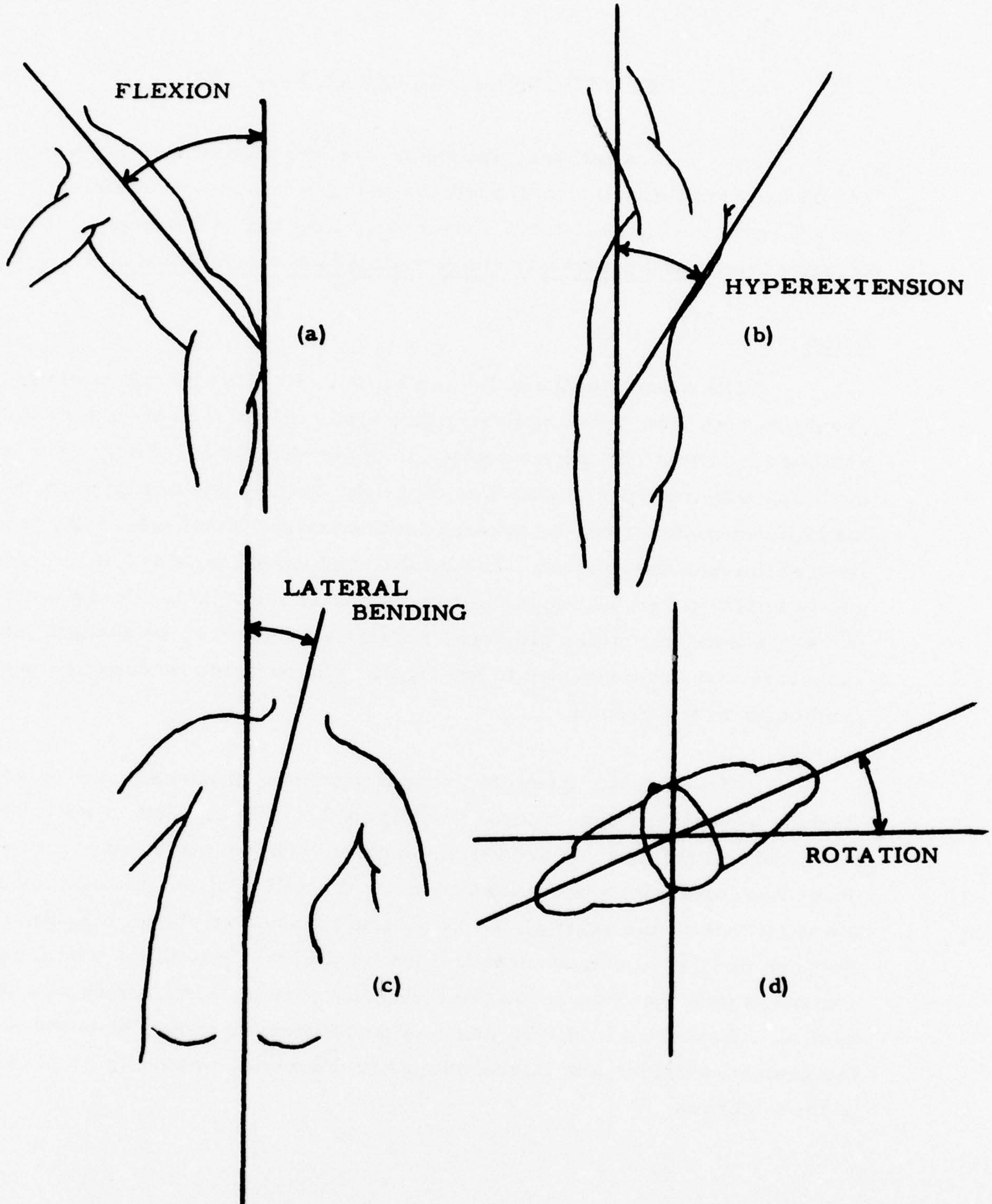


FIGURE 11 MOTION OF SPINE

"Position and Measurement. Motions of the spine should be examined with the patient in the standing, sitting, and lying positions. The sitting position removes the influence of the ham-string muscles on the pelvis. The lying position aids in more accurate localization of pain and an evaluation of muscle tone.

"Flexion is obtained by having the patient bend forward to the limit of function. Flexion is measured by the angle formed by the spine at the axis of motion by the new position of the spine from the neutral position. The average limit of flexion of the spine is about 70°.

"Hyperextension is obtained by the patient bending backward to the limit of function. It is measured by the angle formed at the axis of motion by the backward bending of the spine from the neutral position. The average limit of hyperextension is about 30°.

"Lateral bending is obtained by having the patient bend to the right and to the left to the limit of motion. It is measured by the angle formed by bending the spine to the right and to the left from the neutral position. The average limit of lateral motion to the right or to the left is about 40°.

"Rotation is obtained by the examiner fixing the pelvis with his hands and having the patient rotate the body to the right and to the left. It is measured by comparing the angle made by plane of the shoulders with that of the pelvis. The average limit of rotation of the spine to the right or to the left is 35°.

Shoulder

"The neutral position for the shoulder is with the spine erect and the arms hanging straight down by the sides. This corresponds with the extended and adducted position of zero degrees.

"Movements. From the neutral position, motions which take place are abduction, lateral elevation, flexion, forward elevation, hyperextension, internal and external rotation in the neutral position, internal and external rotation in abduction, (Figure 12) adduction, and circumduction. Movements at the shoulder joint take place between the head of the humerus and glenoid cavity of the scapula together with scapulothoracic, acromioclavicular, and sternoclavicular motion. Once 30° of abduction or 60° of forward flexion is obtained, the relationship of humeroscapular motion remains constant of two humeral to one part scapular motion. Four degrees of elevation of the clavicle takes place for every 14° elevation of the arm up to 90° and none thereafter. About 20° of motion takes place in the acromioclavicular joint throughout the course of abduction. The clavicle rotates upward and backward and the scapula downward and outward during abduction. At the sternoclavicular joint, the clavicle elevates 56°, retracts backward 25°, and rotates 50° on its longitudinal axis.

"Position and Measurement. The patient may stand erect or be seated to examine movement of the shoulder joint. For convenience of the examiner and to evaluate movement in the shoulder, the forearm is flexed to 90°.

"Abduction is obtained by raising the arm straight out and up from the side, and is measured by the angle formed by movement of the arm from the neutral position. The average limit of abduction is 90°.

"Lateral elevation is obtained by continuation of the upward movement of the arm above full abduction of 90° to the limit of motion. This motion is primarily a result of scapulothoracic motion. The average limit of lateral elevation is 40° beyond the 90° of abduction.

"Flexion of the shoulder is obtained by raising the arm straight forward and upward from the neutral position. The average normal limit of flexion is 90°.

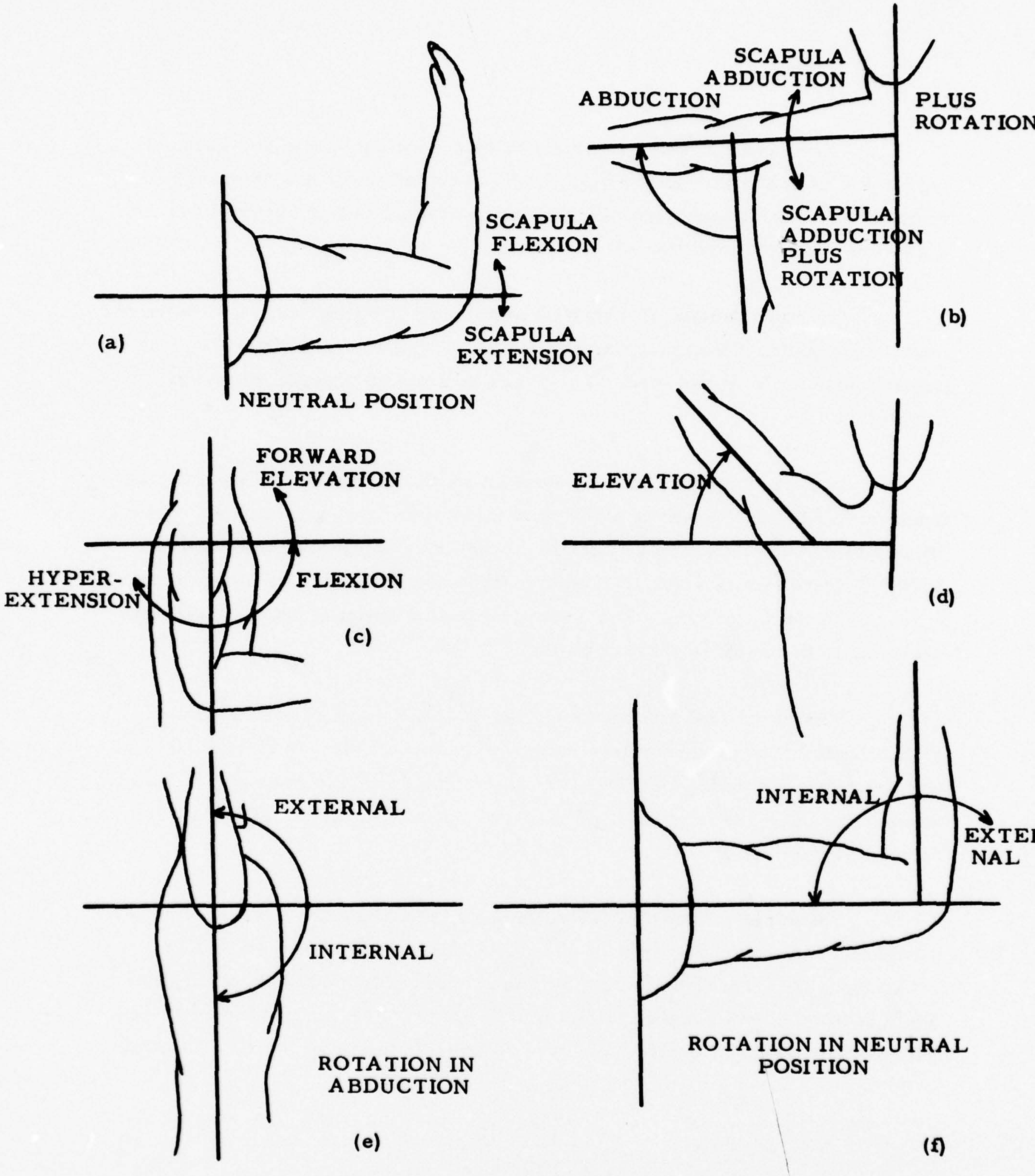


FIGURE 12 MOTION OF SHOULDER

"Forward elevation is obtained by a continuation of the upward movement of the arm. In the completely elevated arm, the clavicle rotates 40° in its longitudinal axis. The average limit of forward elevation is 90° beyond the 90° of flexion.

"Hyperextension is obtained by moving the arm backward from the neutral position. The angle formed by the movement of the arm from the neutral position is measured. The average limit of hyperextension is about 45°.

"Internal rotation of the shoulder in the neutral position if facilitated by flexing the forearm to 90° and turning the forearm inward. Complete internal rotation can be obtained by placing the forearm behind the back. This motion is measured by the angle formed by the forearm moving from the neutral position. The average limit of internal rotation with the shoulder in the neutral position is 90°.

"External rotation of the shoulder in the neutral position is obtained as for internal rotation except that the forearm is turned outward and the angle formed by the forearm in moving from the neutral position is measured. The average limit of external rotation of the shoulder in the neutral position is 45°.

"Internal rotation of the shoulder in the abducted position is obtained by flexing the forearm to 90° to facilitate the movement and its evaluation, the arm is abducted, and the forearm moved downward. The angle formed by the forearm in moving from the starting position is measured. The average limit of internal rotation with the shoulder abducted is 90°.

"External rotation of the shoulder in the abducted position is obtained as for internal rotation except the forearm is moved upward and the angle formed by the forearm moving from the starting position is measured. The average limit of external rotation of the shoulder in the abducted position is 90°.

"Adduction of the shoulder is obtained by moving the arm toward the midline from the neutral position. In the neutral position adduction is prevented by the side of the body, however, about 10° of adduction can be obtained by placing the arm in front or rear of the body.

"Circumduction is accomplished by moving the arm in an arc about the shoulder. It is a succession of the above movements and results in describing a complete circle.

Elbow

"The neutral position for the elbow joint is with the forearm extended and the hand in midposition.

"Movements. From the neutral position, movements of the elbow joint are flexion, hyperextension, supination, and pronation (Figure 13). Flexion and hyperextension occur between the humerus with the radius and ulna.

"Position and Measurement. Flexion is obtained by forward bending of the forearm on the arm. The angle formed by the forearm moving from the neutral position is measured. The average limit of flexion is 145°.

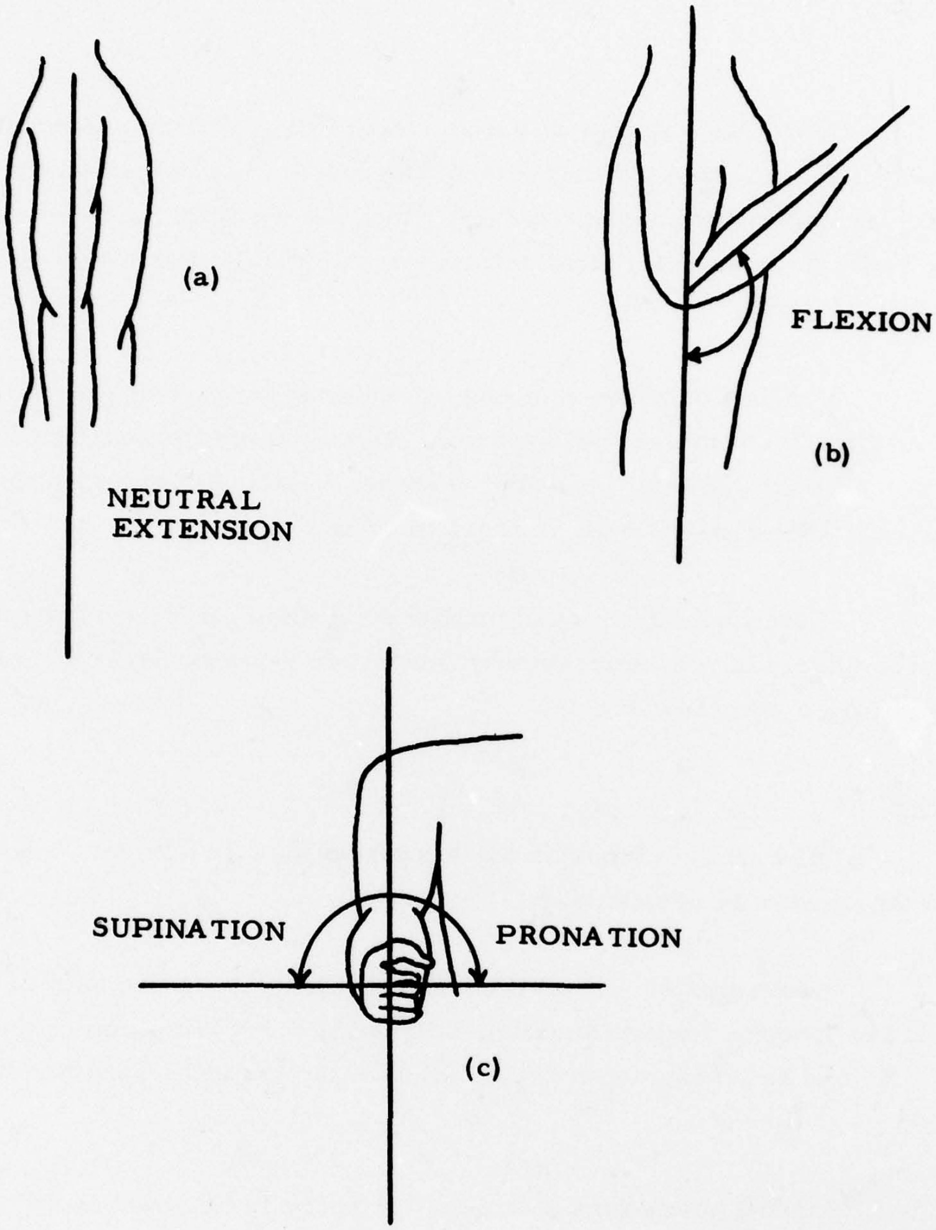


FIGURE 13 MOTION OF ELBOW

"Hyperextension occurs in the same plane as flexion, only it is obtained by moving the forearm backward on the arm from the neutral position and measuring the angle so formed. Normally, there is no hyperextension at the elbow.

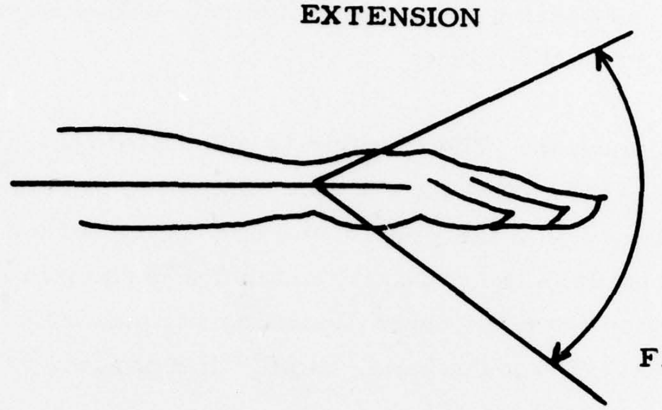
"Supination. The forearm is placed with the ulnar border of the hand down and the radial border up. Supination is obtained by rotating the forearm outward with the palm of the hand being turned up. This motion takes place between the proximal and distal radioulnar. The angle formed by this rotation from the neutral position is measured. The average limit of supination is 90° at the hand, and 60° if measured at the wrist.

"Pronation is measured from the same neutral position as for supination. It is obtained by rotating the forearm inward, turning the palm down. The angle formed by rotation of the forearm and hand from the neutral position is measured. The average limit of pronation is 90° at the hand and 75° if measured at the wrist.

Wrist

"The neutral position for the wrist is with the hand extended in line with the forearm with the palm down.

"Movements. From the neutral position, movements of the wrist joint are palmar flexion, dorsiflexion (dorsiextension), ulnar and radial deviation, (Figure 14). A degree of circumduction is possible at the wrist which is a combination of the above movements. These movements occur primarily between the carpus and radius.



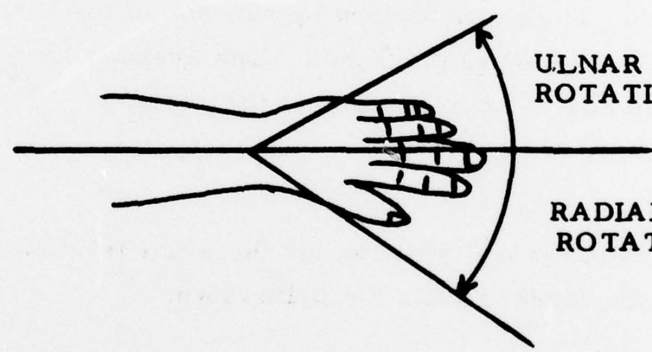


FIGURE 14 MOTION OF WRIST

"Position and Measurement. The wrist is placed in the neutral position with the hand in line with the forearm and with the palm down.

"Wrist flexion is obtained by bending the hand downward at the wrist. The angle formed by this movement of the hand from the extended neutral position is measured. The normal limit of palmar flexion is 70°.

"Extension is obtained by bending the hand upward at the wrist from the neutral position. The angle so formed is measured. The normal limit of dorsiflexion is 65°

"Ulnar deviation is obtained by bending the hand toward the ulnar side. The angle formed by a line down the third finger deviating from the neutral position at the wrist is measured. The average limit of ulnar deviation is 30°.

"Radial deviation is obtained by deviating the hand to the radial side from the neutral position and the angle so formed measured as for ulnar deviation. The average limit of radial deviation is 15°.

Hip

"The neutral position for the hip joint is with the lower extremities in the extended position as in a man standing erect.

"Movements. From the neutral position, movements of the hip joint are flexion, hyperextension, abduction, adduction, internal and external rotation in extension, internal and external rotation in flexion, and circumduction (Figure 15). Movement takes place between the head of the femur and the acetabulum.

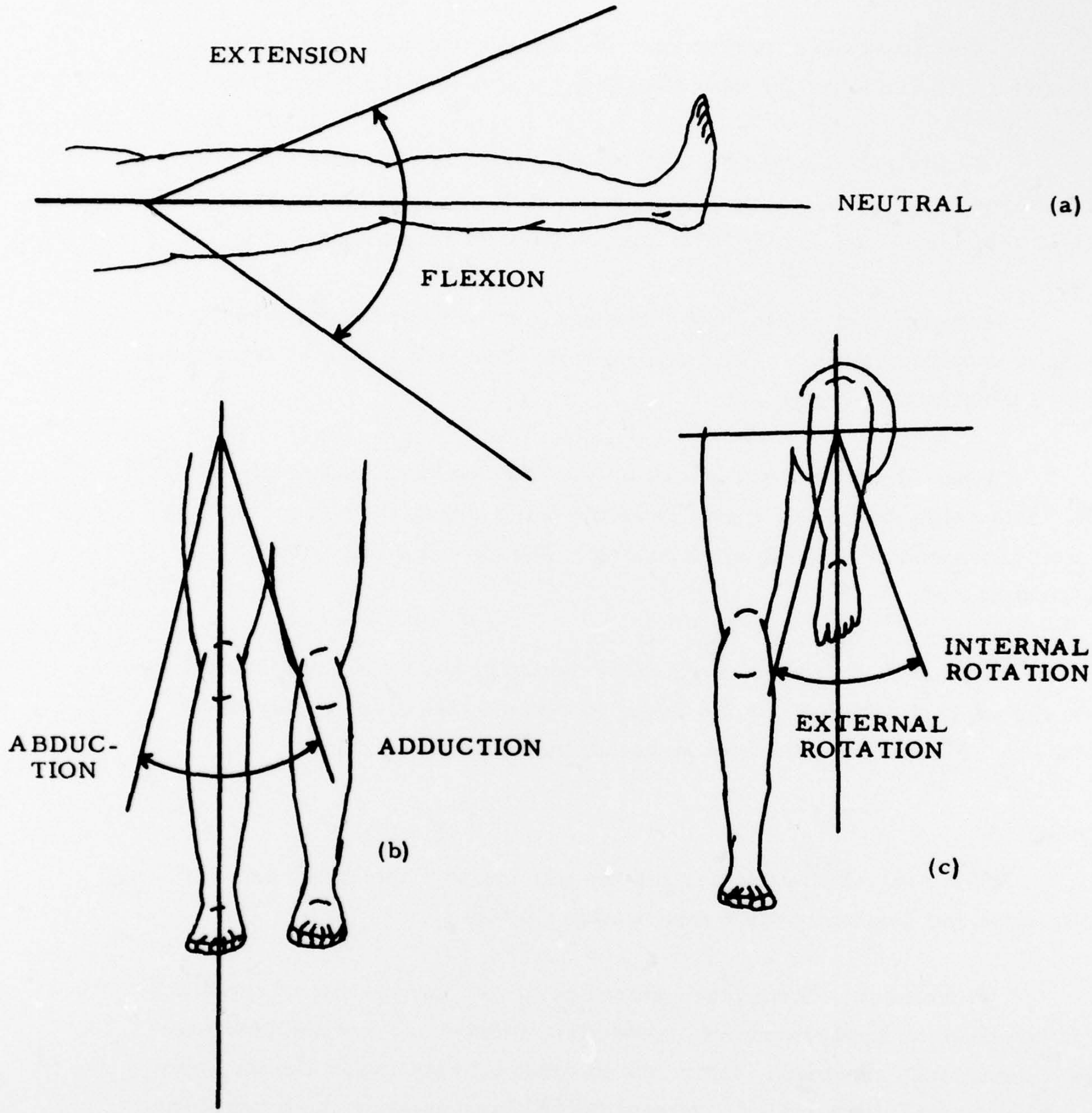


FIGURE 15 MOTION OF HIP

"Position and Measurement. For ease of examination, the patient is placed supine on an examining table. All movements except hyperextension, which is performed in the prone or lateral position, can be determined in this position. Abduction may also be performed in the lateral decubitus position.

"Flexion. With the patient lying flat on his back with his legs straight, flexion is obtained by bringing the thigh forward and upward toward the abdomen. The angle formed by the thigh moving from the neutral position is measured. The average limit of flexion of the hip is 120°.

"Any limitation of complete extension of the hip should be recorded in degrees of permanent flexion. In order to obtain this measurement, with the patient supine, the opposite hip is flexed on the abdomen until the lumbar vertebrae are flat with the table. The angle formed by the femur with the horizontal line representing the neutral position is recorded as degrees of permanent flexion.

"Hyperextension is obtained with the patient lying prone or in the lateral decubitus position. The thigh is moved backward from the neutral position. The angle formed by this movement from the neutral position is measured. The average limit of hyperextension is 45°.

"Abduction is obtained either in the lateral decubitus or supine position. The thigh is moved outward from the neutral position. The angle formed by this movement from the neutral position is measured. The average limit of abduction is 45°.

"Adduction is obtained by moving the thigh across the midline from the neutral position. The angle so formed by this movement is measured. The average limit of adduction is 40°.

"Internal rotation in extension can readily be obtained with the patient in the prone position. The knee is flexed to 90° and the leg and foot rotated outward. The angle formed by the leg moving from the vertical neutral position is measured. The average limit of internal rotation in extension is 20°.

"External rotation in extension is obtained in a manner similar to that for internal rotation except the leg and foot are rotated inward. The angle formed by the leg moving from the neutral position is measured. The average limit of external rotation in extension is 35°.

"Internal rotation in flexion. With the patient supine the hip and knee are each flexed to 90°, the leg and foot are rotated outward. The angle formed by the leg moving from the neutral position is measured. The average limit of internal rotation in flexion is 30°.

"External rotation in flexion is obtained in a manner similar to internal rotation except the leg and foot are rotated inward and the angle so formed measured. The average limit of external rotation in flexion is 60°.

"Circumduction of the hip is a succession of the above movements obtained by describing an arc with the thigh through the extremes of the various movements of the hip joint.

Knee

"The neutral position for the knee joint is with the leg in a straight line with the thigh in the extended position (Figure 16).

"Movements. From the neutral position movements of the knee are flexion and hyperextension. These movements occur at the articulation between the femur and the tibia. In addition to these movements lateral and anteroposterior stability of the knee joint should be tested.

"Position and Measurement. These movements may be measured with the patient sitting on the edge of an examining table or lying supine on the table.

"Flexion is obtained by bending the leg backward toward the posterior surface of the thigh. In the supine position, this is facilitated by flexion of the hip. The angle formed by the leg moving posterior from the neutral position is measured in degrees. The average limit of knee flexion is 135°.

"Hyperextension is obtained by holding the thigh firm on the examining table and lifting the leg anteriorly from the neutral position. The angle formed by movement of the leg from the neutral position is measured and recorded. There is normally no hyperextension of the knee joint.

"Lateral stability is obtained by moving the leg first laterally then medially from the neutral extended position. Any deviation should be recorded as mild, moderate, or severe. This is a test for the medial and lateral collateral ligaments of the knee.

"Anteroposterior stability is obtained by flexing the knee to 90° to relax the collateral ligament. The leg is grasped and pulled directly anterior. This is a test of the status of the anterior cruciate ligament. This leg is returned to its normal position and the leg then pushed posteriorly to test the stability of the posterior cruciate ligament. Abnormal motion is recorded as mild, moderate, or severe.

Ankle

"The neutral position for the ankle is with the lateral border of the foot at 90° with the axis of the leg and in midposition as regards to inversion and eversion (Figure 17).

"Movements. From the neutral position the movements of the ankle are plantar flexion and dorsiflexion (extension). These movements take place at the articulation between the tibia and talus and should be compared with the knee in the extended position and with the knee flexed at 90° to rule out limitation of motion due to a tight gastrocnemius or soleus muscle.

"Position and Measurement. The patient may be sitting or lying supine on the examining table.

"Plantar flexion is obtained by moving the foot downward from the neutral position. The angle formed by the lateral border of the foot moving from the neutral position is measured in degrees of plantar flexion. The average limit of plantar flexion of the ankle is 35°.

"Dorsiflexion of the ankle is obtained by moving the foot upward from the neutral position. The angle formed by the lateral border of the foot moving from the neutral position is measured in degrees of dorsiflexion. The average limit of dorsiflexion is 20°.

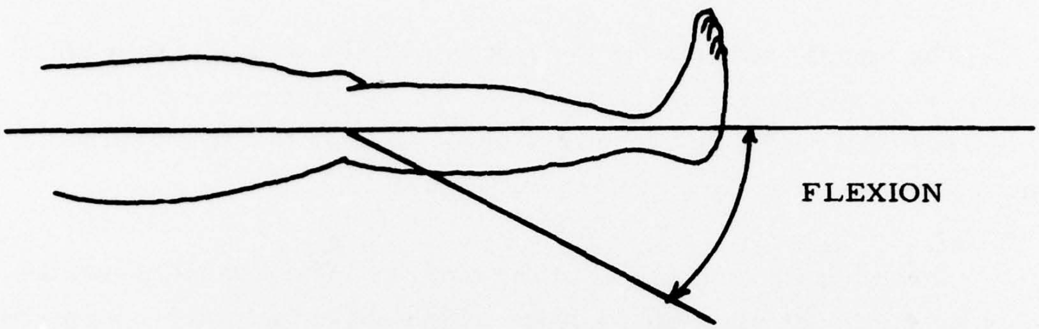


FIGURE 16 MOVEMENT OF KNEE

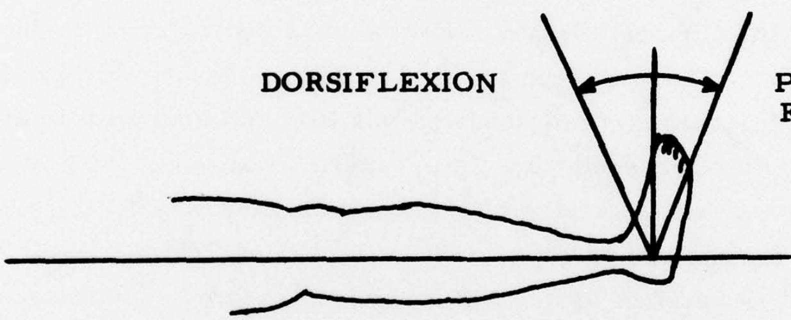


FIGURE 17 MOVEMENT OF ANKLE

Foot

"The neutral position for the foot is with the os calcis in neutral position as regards inversion and eversion and with a line bisecting the heels, extending through the second toe perpendicular to a line representing the posterior surface of the heel (Figure 18).

"Movements. Movements of the foot are inversion and eversion which occur in the subtalar joint; adduction and abduction which take place in the midtarsal joints; flexion and hyperextension of the metatarsophalangeal joints, which in the great toe is the most important; and interphalangeal joint motions of flexion and hyperextension which are very difficult to measure.

"Position and Measurement. Inversion is the inward deviation of the os calcis which normally is 35°. Eversion is the outward deviation of the os calcis and can normally be carried to 25°. Adduction is the inward deviation of the forefoot from the neutral position and normally is about 5°. Abduction is the outward deviation of the forefoot which is also about 5°. Metatarsophalangeal and interphalangeal joint motion is of little importance except in the great toe where, normally, it is 35° of flexion and 20° of hyperextension. Pronation of the foot is a combination of eversion and abduction which may normally be 15°. Supination is a combination of inversion and adduction and normally is 20°."

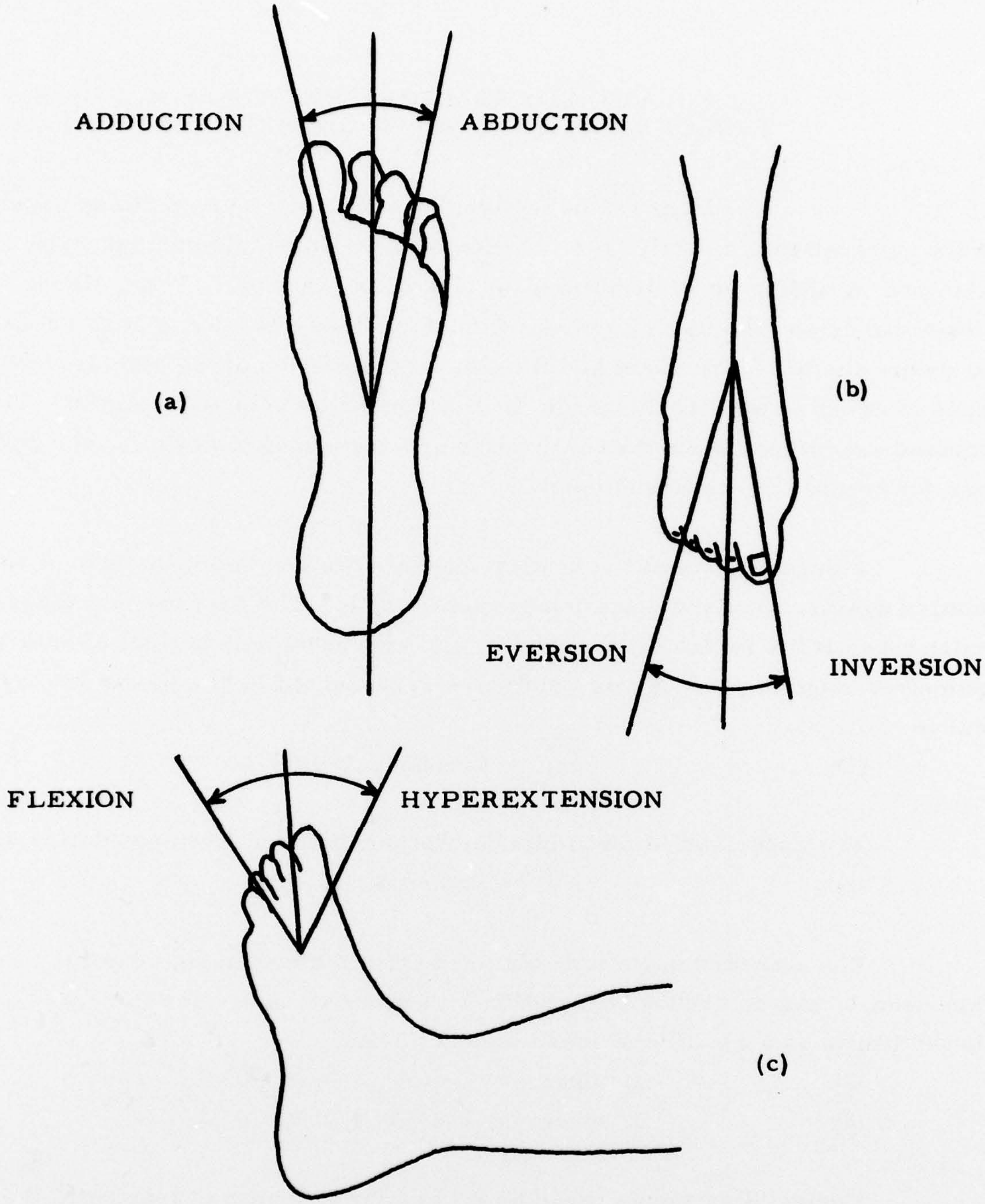


FIGURE 18 MOTION OF FOOT

8.3 CALCULATION OF STANDARD DEVIATION AS A FUNCTION OF MEAN LENGTH FOR ANTHROPOMETRIC DATA

As discussed in Section 5.2, certain required dimensions were not available directly from the literature. These dimensions were obtained by adding or subtracting data that were available. Thus, if two mean values and the associated standard deviations are known, it is necessary to determine the mean value and the standard deviation of the sum or difference in order to specify the range for the dimension being considered. The method used to calculate the mean value and the standard deviation for sums and differences is discussed below.

Figure 19 presents a scatter diagram for lengths of the human body plotted against standard deviation per unit length. The data for this diagram were taken from Tables 4, 6, 7 and 8, and represent data typical of anthropometric lengths. These data points are represented by the linear regression curve

(1) $$\sigma/L = 0.0628 - 0.000427\ L.$$

The upper and lower limits for 90 percent of a given population are

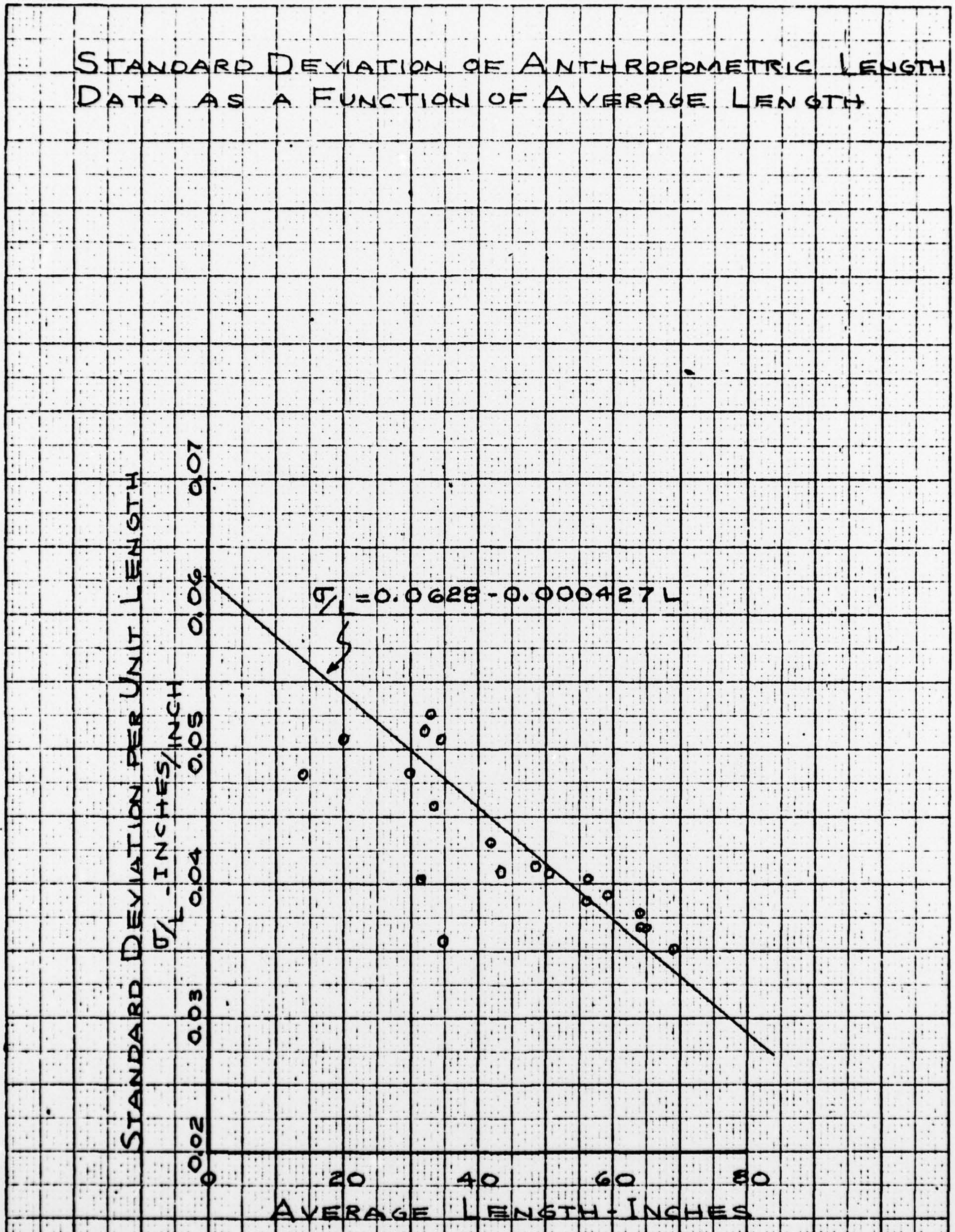
(2) $$L = L\ \text{mean} \pm 1.645.$$

The standard deviation, obtained from the regression curve, Equation 1, can be used with Equation 2 in order to determine the upper and lower limits as a function of mean length. Thus,

(3) $$L\ \text{upper} = 1.103L \quad -0.000703\ L^2,\ \text{and}$$

(4) $$L\ \text{lower} = 0.897\ L + 0.000703\ L^2.$$

Figure 20 presents these upper and lower limits of lengths of the human body as functions of the mean length. The exoskeleton must be adjustable to the limits specified by Figure 20 in order to be wearable by 90 percent of the adult, male population.



STANDARD DEVIATION OF ANTHROPOMETRIC LENGTH DATA AS A FUNCTION OF AVERAGE LENGTH
σ/L =0.0628-0.000427L
STANDARD DEVIATION PER UNIT LENGTH
σ/L -INCHES/INCH
0.07
0.06
0.05
0.04
0.03
0.02
0
20
40
60
80
AVERAGE LENGTH-INCHES

FIGURE 19

UPPER AND LOWER LIMITS OF ANTHROPOMETRIC LENGTH DATA VERSUS MEAN LENGTH

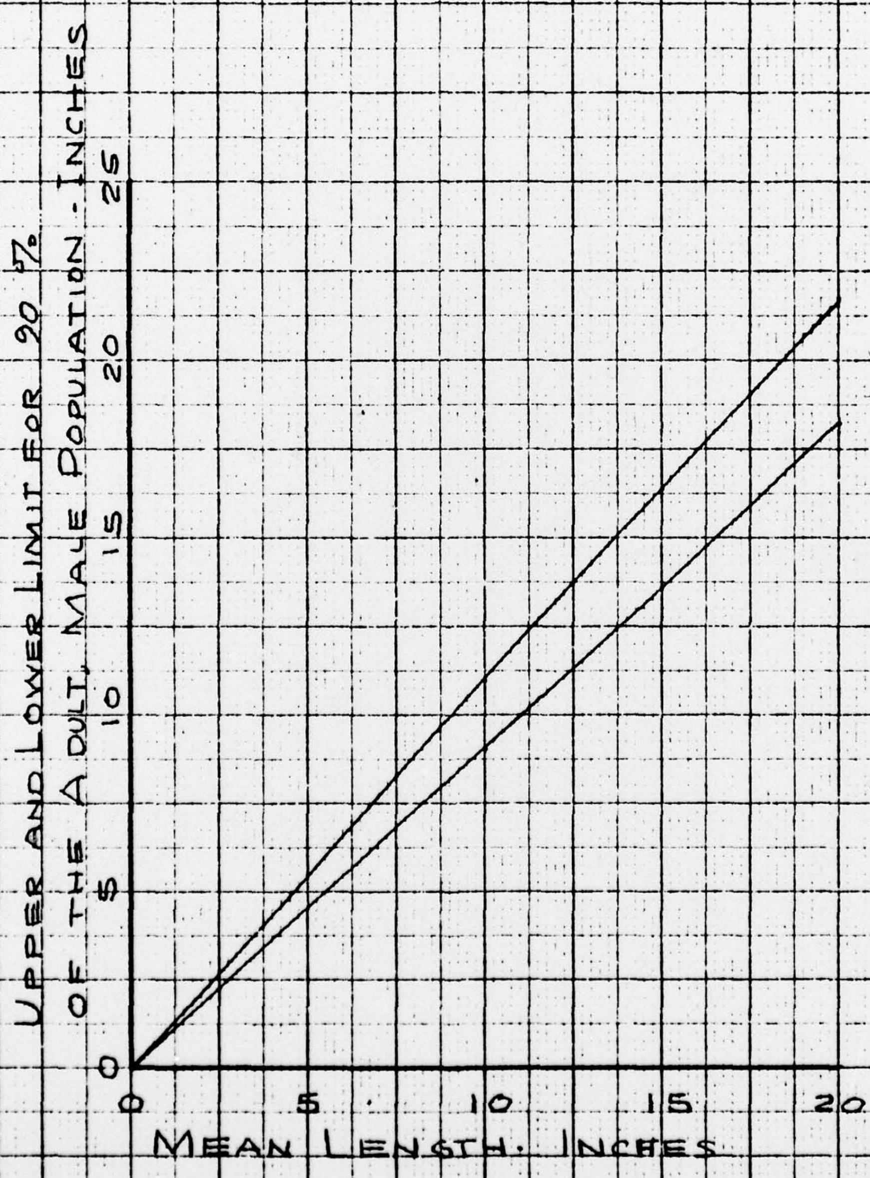


FIGURE 20